THE JOURNAL

OF

"The Royal Aeronautical Society"

with which is incorporated "The Institution of Aeronautical Engineers"

Edited for the Council by Captain J. LAURENCE PRITCHARD, Hon. Fellow

No. 210. JUNE, 1928. Vol. XXXII.

NOTICES

President and Vice-Presidents

At a meeting of Council held on May 8th, 1928, Colonel the Master of Sempill, A.F.C., A.F.R.Ae.S., was unanimously elected President of the Royal Aeronautical Society with which is incorporated the Institution of Aeronautical Engineers for the ensuing year, 1928-29. The Master of Sempill, after serving some years on the Council of the Royal Aeronautical Society, was unanimously elected its Chairman for 1926-27, a period extended by a special rule so that continuity during the period of negotiations with the Institution of Aeronautical Engineers should be maintained. In January, 1928, the amalgamated body came into full being with a completely revised set of rules, among which was one stating that a President should be appointed, together with one or more Vice-Presidents.

At the same Council Meeting Air Vice-Marshal Sir Vyell Vyvyan, K.C.B., D.S.O., and Lieut.-Colonel J. T. C. Moore-Brabazon, M.C., M.P., were elected Vice-Presidents for the year 1928-29.

Banquet to Mr. A. V. Roe

As already announced in the Journal, a banquet, to be followed by a dance, is being given to Mr. A. V. Roe by the Royal Aeronautical Society, the Royal Aero Club, the Air League of the British Empire, and the Society of British Aircraft Constructors, in recognition of Mr. A. V. Roe's services to aviation.

The banquet, which will be held at the Savoy Hotel, at 7.30 p.m. for 8 p.m., on June 8th, will be attended by many distinguished people who have signified their intention of being present to honour Mr. Roe. These include Sir Samuel Hoare, the Air Minister, and members of the Air Council, the leading designers and pioneers, and representatives of foreign Governments and the British Dominions.

H.R.H. the Duke of York has graciously consented to be present during the evening.

The chair at the banquet will be taken by Sir Charles Wakefield.

As the number of tickets (price £1 1s. 0d., including dance) is limited, early application is advised.

Postponement of Lecture

The lecture by Dr. Rudorf on Testing Aircraft Materials, announced for May 24th, has been postponed until the next Session, the extremely arduous duties of Dr. Rudorf at the present time making it impossible for him to prepare it for this Session.

Portrait of Sir Arthur Whitten Brown

An oil painting of Sir Arthur Whitten Brown, who, with the late Sir John Alcock, was the first to fly the Atlantic in a heavier-than-air machine, has been lent to the Society on permanent loan by Messrs. Rolls-Royce, Ltd. The painting, by Ambrose McEvoy, is hung in the Council Chamber.

Elections

The Council considered the report of the Grading Committee and the following elections were made:—

Fellow (transferred from Associate Fellow).—Mr. E. P. Warner.
Associate Fellows.—Mr. A. H. Shirwall and Commander S. Yamasita, I.J.N.
Associate.—Mr. T. A. Gibson.
Student.—Miss D. M. Hirst.
Companions.—Mrs. Fullerton and Mr. R. C. Joynson-Hicks.

Address to Institution of Civil Engineers

On the occasion of the Centenary Celebrations of the Institution of Civil Engineers this month a suitable address of congratulation has been prepared on behalf of the Society.

Special Lectures

A lecture will be given by Lieut. R. R. Bentley on the Technical Aspects of his African Flight on Friday, June 1st, at 6.30 p.m., at the Royal Society of Arts.

A lecture will be given on Thursday, June 14th, by Captain Wilkins, on his Polar Flight. The lecture will be held at the Royal Society of Arts, 18, John Street, Adelphi, W.C.2, at 6.30 p.m.

The President's Guests

During the Session the President, Colonel the Master of Sempill, has entertained to dinner a number of members of the Society and others after lectures.

The following were the President's guests at the Junior United Service Club after the lecture by Wing Commander R. M. Hill on March 1st:—Wing Commander Hill, Sir Arnold Wilson, Dr. Dunstan, Mr. Coxon, Major Stewart, Major Turner, Major Mayo, Mr. Colebrook, Mr. Wimperis, Lord Thomson, Brig.-General Groves, Mr. Handley Page, Captain Acland, Sir Vyell Vyvyan.

After the lecture by Flight-Lieutenant Cross, on March 15th, a dinner was held at Junior United Service Club at which the President's guests were:—Flight-Lieutenant Cross, Wing Commander Maycock, Mr. Oswald Short, Mr. A. Gouge, Mr. Lankester Parker, Major Rennie, Flight-Lieutenant Comper, Squadron-Leader Scott, Major Brackley, Captain Sayers, Major Sippe, Mr. Manning, Mr. Chorlton, Mr. Fairey.

The President's guests following the lecture by Dr. Eng. Herr C. Dornier on April 25th were as below. The dinner was held at Junior United Service Club:—Dr. Dornier, H.E. the German Ambassador, Dr. Dieckhoff, Major Bumpus, Mr. Bramson, Major Buchanan, Captain Acland, Colonel O'Gorman, Major Penny, Mr. A. V. Roe, Mr. Mitchell, Mr. Michael Perrin, Major Low, Major Ledeboer, Mr. O. Short, Mr. Fairey, Major Rennie.

On May 10th, following the lecture by Mr. B. N. Wallis, a dinner was given at Junior United Service Club, at which the following were the guests:—Mr. B. N. Wallis, Mr. R. Blackburn, Captain F. L. M. Boothby, Sir Sefton Brancker, Mr. Griffith Brewer, Wing Commander T. R. Cave-Browne-Cave, Mr. A. E. L. Chorlton, Colonel L. F. R. Fell, Group Captain P. F. M. Fellowes,

Air Commodore E. A. D. Masterman, Mr. J. D. North, Lieut.-Colonel V. C. Richmond, Major G. H. Scott, Mr. H. T. Tizard, Sir Vyell Vyvyan.

Associate Fellowship and Membership Examinations

Provided a sufficient number of entries are obtained the examinations for Associate Fellowship will be held in the week beginning Monday, September 17th, and those for Associate Membership in the week beginning Monday, September 24th. Candidates should advise the Secretary as soon as possible of their intention to take the examination, so that the necessary arrangements can be made.

Forthcoming Arrangements

Friday, June 1st.—Lecture by Lieutenant R. R. Bentley, of the South African Air Force, on Technical Aspects of his South African Flight, at the Royal Society of Arts, at 6.30 p.m.

Friday, June 8th.—Banquet to Mr. A. V. Roe, at the Savoy Hotel, at 7.30 for 8 p.m. The banquet will be followed by a dance.

June 14th.—Lecture by Captain Wilkins on his Polar Flight, at the Royal Society of Arts, at 6.30 p.m.

J. Laurence Pritchard, *Secretary.*

OBITUARY

Jacques Schneider

It is with deep regret that the Council have to record the death of M. Jacques Schneider.

M. Jacques Schneider is assured of an imperishable name in aviation as the donor of the Jacques Schneider Seaplane Trophy. He was a member of a famous family of armament manufacturers, and one of the pioneers of aviation, obtaining his pilot's certificate in 1909 as a pupil of M. Louis Bleriot. Four years later he presented his now world-famous trophy to the Aero Club de France for international competition. At the time of his death at Beaulieu, in the South of France, M. Jacques Schneider was a member of the Executive Committee of the club. By his death France loses one of its most distinguished aviation enthusiasts, and a man who gave as great an encouragement to aviation as any man in the world. During his lifetime M. Schneider saw the speed of seaplanes winning his trophy increase from 44.7 to 281.48 m.p.h., this remarkable increase in figures alone indicating the advance in seaplane and engine design due to the spirit of international rivalry fostered by the donor of the Schneider Seaplane Trophy.

CORRESPONDENCE

To the Editor of the JOURNAL OF THE ROYAL AERONAUTICAL SOCIETY.

SIR,—Several emotions conflict on reading pages 241 to 243 of your issue of April, 1928, which you courteously sent me. The spectacle of my statement sandwiched between your salutatory and Mr. Griffith Brewer's valedictory has a Daniel-in-the-lion's-den aspect that amuses one, while arousing other impressions. It has been sufficiently obvious for several years that nothing the Smithsonian could do or leave undone would meet with Mr. Griffith Brewer's approbation, but I confess surprise that you, Sir, should have thought fit to prejudice your readers in advance against my proposal by your introduction:—"... after the death of Professor Langley, Secretary of the [Smithsonian] Institution. A campaign was begun to take from the Wrights credit, which had up to then never been disputed. ... In view of the importance of combating the unfounded and ungenerous attacks on the achievement of the Brothers Wright, the circular notice recently received by the Editor is published here. ..."

If it is insisted that the Smithsonian Institution must confess to knavery before this controversy can be settled, we dismiss the subject. I, indeed, regret that it was thought wise either to make the experiments of 1914 or to claim priority for Langley's heavier-than-air machine of 1903 as the first capable of sustained free flight carrying a man. I have never doubted that only bad luck prevented its success on October 7, 1903, but as this must always remain a matter of opinion, I regret that the claim was made: First, because it has wounded the sensibilities and seemed unfair to Mr. Orville Wright, whom I have met in most friendly fashion, and admire as a gallant, lovable, able pioneer, who with his brother mastered the problem independently by their own experiments; second, because the Smithsonian Institution, which deserves public respect and confidence, has suffered thereby gross misrepresentation and vituperation.

There is nothing which hinders me from going very far to satisfy Mr. Wright and close this unfortunate episode except the insistence that we confess ourselves to be insincere knaves. You may judge if this charge is true when I recall to you the following facts:—

1. Langley himself said after the two unsuccessful launchings: "Failure in the aerodrome itself or its engines there has been none; and it is believed that it is at the moment of success, and when the engineering problems have been solved, that a lack of means has prevented a continuance of the work." He died in the same belief.

2. Manly twice risked his life in this faith, and eagerly wished to risk it thus again. From conversation I had with him in 1925, I am certain that he also died in the same belief.

3. Chanute on several occasions stated that "he had no doubt" that Langley's machine "would have flown if it had been well launched into the air."

4. Walcott in 1925, after the publication of Mr. Griffith Brewer's celebrated attack, wishing to correct any mis-statement, asked Messrs. Ames and Taylor, eminent, disinterested students of aviation, now Chairman and Vice-Chairman, respectively, of the National Advisory Committee for Aeronautics, to examine the circumstances. They did so, and, in a report released for publication June

9, 1925, sustained the claim, but suggested that it be modified to read merely a statement of opinion, which was done. Walcott died believing the claim.

I have asked Mr. Wright nothing more than the recognition that those who represent the Smithsonian are honest in this belief, as a necessary preliminary to concessions from the Institution. Without the recognition of the honesty of the Smithsonian Institution from him, any move I might be glad to make would be seized upon by detractors to brand the Institution as pusillanimous as well as knavish.

I am, Sir, yours faithfully,

C. G. ABBOT,

Secretary, Smithsonian Institution.

April 27th, 1928.

[Dr. Abbot appears to have overlooked the fact that his original statement, published in the April number of the Journal, was written by him for the American Press and required an editorial note to introduce it over here. Ten days after the date of Dr. Abbot's statement, the Board of Regents of the Smithsonian Institution passed a solemn resolution declaring that the Wrights were the first to fly. It is evident that they did not formerly concede this fundamental fact, and therefore it should be easy for Dr. Abbot—pleading the innocence and not the knavery of the Smithsonian as the cause of his unwelcome inheritance—to withdraw the past misleading propaganda.

My introductory note has drawn the very generous statement from Dr. Abbot, however, of admiration for Mr. Orville Wright as "a gallant, lovable, able pioneer, who with his brother mastered the problem independently by their own experiments." We are now apparently in agreement, and the way can surely be found to bury the bone of contention so deeply that it may never be resuscitated.—EDITOR.]

The Secretary,
The Royal Aeronautical Society,
7, Albemarle Street, London, W.1.

DEAR SIR,—In the Journal of the Society for May there is a communication from Mr. Simmonds in which he criticises adversely the part of my lecture dealing with range.

In the first place, the subject of the lecture was not the determination of the maximum range of flying boats, but on matters relating to the Problem of the Long Range Flying Boat. An endeavour was made to show, by means of characteristic curves, the main factors on which range and cruising speed depend.

In Fig. 1 the ranges were calculated using an average figure for the air miles per gallon, which figure was obtained not by rough calculation, as mentioned by Mr. Simmonds, but by estimating the air performance at various loads, and hence by means of the propeller and engine characteristics, using mixture control, the consumption at the most economical speed was obtained.

To obtain the range integration was found to be unnecessary, as the air miles per gallon varied linearly with the weight. At the heaviest loads I admit the ranges given are probably on the high side, but at these loads the boat could not take off. For the purpose in view, the ranges shown in Fig. 1 for weights from 24,000 lbs. to, say, 37,000 lbs. are of sufficient accuracy and agree with those given by Mr. Simmonds, as there is no reason to accept his figures as being strictly accurate, although he works out the range to within one sixth of one per cent.

Now, with regard to the question of the relation between the air miles per gallon and the weight, the fact remains that the relationship is linear over a considerable variation in weight, when mixture control is used. Extensive consumption tests have been carried out on Iris II. by the Air Ministry, and the results definitely show the air miles per gallon to vary linearly with the weight, with sufficient accuracy for all purposes, over the range from 24,000 lbs. to 33,000 lbs., and further, over this weight variation the economical speed remains constant.

Yours faithfully,

J. D. RENNIE.

PROCEEDINGS

FIFTH MEETING, FIRST HALF, 63RD SESSION

The Fifth Meeting of the Sixty-Third Session of the Royal Aeronautical Society (with which is incorporated the Institution of Aeronautical Engineers) was held in the Theatre of the Royal Society of Arts, 18, John Street, Adelphi, W.C.2, on Thursday, November 24th, 1927, when Major C. J. Stewart, O.B.E., M.I.Mech.E., F.R.Ae.S., M.I.A.E., read his paper on "Modern Developments in Aircraft Instruments." Colonel the Master of Sempill (Chairman of the Society) was in the Chair.

Colonel the MASTER OF SEMPILL: The lecture this evening will be of particular interest. The last one which we had on this subject was delivered by Mr. Wimperis, the Director of Scientific Research.

Major Stewart before the war was one of the Inspectors of Engineering Schools and Colleges, and Lecturer in Physics and Engineering, and during part of the war he was Chief Experimental Officer at the old Orfordness Station. For the past few years he has been in charge of experimental work at the Royal Aircraft Establishment, South Farnborough, and has been engaged in designing and developing many instruments. The development of instruments is of great importance, and we have just had a very fine example of what can be done by their use. I refer to the case of Captain McIntosh and Mr. Hinkler, who in their recent flight were in the air for some 18 hours, flying by their instruments alone, in dense clouds.

I now have much pleasure in calling upon Major Stewart to read his paper.

MODERN DEVELOPMENTS IN AIRCRAFT INSTRUMENTS

BY MAJOR C. J. STEWART, O.B.E., M.I.MECH.E., F.R.AE.S., M.I.A.E.

Introduction

It is now four years since the Society had before it a paper devoted exclusively to developments in aircraft instruments,* and it is perhaps time to review the changes which have taken place.

It will be clear that in the effort to make as wide a review as the time and space at our disposal permit, it will not be possible to do much more than to deal with the more important improvements.

The aim of the present paper is to describe some of the post-war developments in instrument design brought about by the demand for the more accurate measurement of aircraft performance and by the need for measuring more accurately those conditions which hitherto have been somewhat unfaithfully recorded by the instruments of earlier design. Notably, redesign has been called for in almost every case to meet the extension of those conditions, particularly that of temperature. An endeavour has been made to bring out the more important changes which have taken place in each particular type of aircraft instrument, and purely experimental and comparatively untried modifications have been omitted. By this means it is hoped to evade the criticism

* Some Recent Developments in Aircraft Instruments, by Major H. E. Wimperis, M.A., F.R.Ae.S.

that the changes described are of the nature of shadows rather than substance. The demand that nearly all aircraft instruments must function, and in most cases accurately measure, under a range of temperature from +60°C. to −60°C. has profoundly affected design and caused an appreciable amount of trouble to manufacturers. In the evolution of modern designs advantage has been gained by the new orientation of outlook consequent upon the clearer division between research and development. Some of the work to be described has been carried out at the Royal Aircraft Establishment, and notable advance has been made in many instruments by those firms to whose patience and initiative the industry owes a debt. It is worth remarking that the firms engaged in producing new designs of aircraft instruments are in a somewhat peculior position, for the amount of costly experimental work they are sometimes committed to in the evolution of new designs, bears such a relation to the commercial value of the completed instrument that the virtue of financial optimism must at times be sorely tried.

Types of Instruments

It is proposed to deal with the following types of instruments:—

1. Altimeters.
2. Air speed indicators.
3. Statoscopes.
4. Climb meters.
5. Turning indicators and altitude indicators.
6. Thermometers.
7. Pressure gauges.
8. Revolution indicators.
9. Fuel flow meters.
10. Fuel contents gauge.
11. Compasses.
12. Drift indicators.

A description of recent work on capsules for diaphragm instruments is also given as affecting design.

The developments in the design of magnetic compasses have already been placed before the Society.

The gyroscopic compass for aircraft is not dealt with in the present paper for the reason that it has not yet been fully developed.

No reference has been made to oxygen and other high altitude appliances which may be reasonably regarded as falling within the scope of a paper dealing with aircraft instruments, for it is considered that they may be more adequately dealt with in a separate paper.

Fog landing instruments and instrumental safety appliances have been dealt with at previous meetings of the Society, and aerial sextants have been described by Mr. Booth, at the Optical Convention, 1926.

Altimeters

In describing the developments in the technique of altimetry it is worth while briefly to review the theory of the subject to explain more clearly the reasons for the various steps in design, and the writer hopes that he may be forgiven for referring to one or two elementary aspects of the problem.

The method of measuring height which is used on aeroplanes is virtually to weigh a column of air and from a knowledge of its density to deduce its height. An aneroid is used to measure the difference in pressure between the top and bottom of an air column of unit area, and if the temperature at all heights between the top and bottom of the column were known, all the data necessary to compute

the height would be available. Various assumptions have been made regarding the relationship between height and temperature so as to provide a basis of design for altimeters, but as will be clear from Fig. 1, which shows the average yearly and seasonal extreme height-temperature curves, no such assumption can form an exact description of the conditions prevailing on any given occasion. Observations with exploring balloons taken in many parts of the world indicate that although the temperatures near the ground vary very considerably the average lapse rate in the troposphere does not vary much from 2°C. per 1,000 feet, and thus a computer which assumes a standard lapse rate line positioned by one observed temperature will increase the accuracy of an aneroid reading considerably.

Four conventions regarding the relation between height and temperature have been used in various designs of altimeters or computers:—

1. The temperature of the air is constant. This is the basis of the isothermal altimeter, the temperature being assumed to be +10°C.
2. The temperature is a linear function of the height and can be expressed by a standard ground temperature and a standard lapse rate. This is the I.C.A.N. convention.
3. The temperature can be expressed by the actual ground temperature and a standard lapse rate. For greater precision the ground temperature is assumed to be about 3°C. above the observed ground temperature. The reason for this is clear from Fig. 1.
4. The temperature can be expressed by the actual temperature at the height and a standard lapse rate.

Clearly the first two assumptions must give rise to large errors depending on locality and season.

The I.C.A.N. convention,* for example, according to yearly average conditions will enable height computation to be made within 1 per cent., but the error due to seasonal changes may be from +3 per cent. to −3 per cent. for England.

For a reference atmosphere for performance purposes a better agreement could hardly be achieved.

As a basis of calibration for altimeters the convention cannot be considered to meet the requirements of an instrument to measure height accurately. Indeed, with the instrumental errors known to exist in the older types of instrument, an altimeter ranged to about 9,000 feet based on (1) would be nearly as accurate as one based on (2) when seasonal changes are taken into account. Above this height the second assumption gives an increasing advantage in accuracy. Considerable ingenuity has been displayed in designing computers to give the height based on the assumptions given in (3) and (4). Two forms of dial have been

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* On the assumption of a uniform lapse rate $\theta=\theta_1-\sigma h$.

where θ_1 = ground temperature, absolute.
θ = absolute temperature at a height h metres.
σ = lapse rate in degrees per metre.

It can be shown that

$$P/P_o=\{(\theta_1-\sigma h)/\theta_1\}^{1/c\sigma}.$$

where P_o = ground pressure.
P = pressure at height h metres.
c = a constant.

Using the data 1 cu-cm of air at a pressure of 1013.2 m.b. in latitude 45 (g=980.62) weighs 0.001247 gms. at a temperature of 10° C. the value of c is found to be 27.278.

This formula is the general formula for any ground temperature and any lapse rate. The S.T.Ae., or as it is now called, the I.C.A.N. Convention, is calculated as shown; the lapse rate chosen is that shown by such a line as *F G* (Figure 00), *i.e.*, a lapse rate of 6.5° C. per kilometre, but the ground temperature is taken as 15° C., *i.e.*, 288 absolute.

This gives the formula $P/P_o=\{(288-.0065\,h)/288\}^{5.256}$.

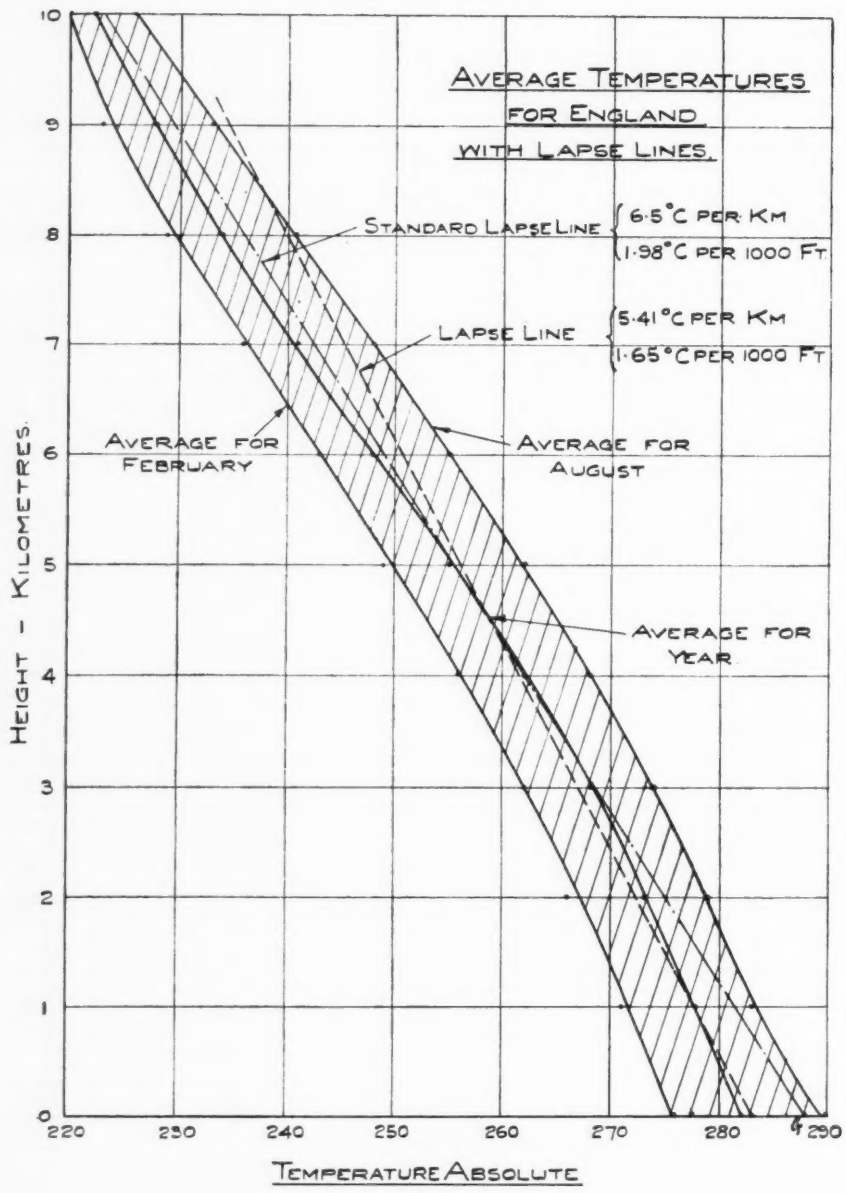
AVERAGE TEMPERATURES
FOR ENGLAND
WITH LAPSE LINES.
STANDARD LAPSE LINE
6·5°C PER KM
1·98°C PER 1000 FT
LAPSE LINE
5·41°C PER KM
1·65°C PER 1000 FT
AVERAGE FOR FEBRUARY
AVERAGE FOR AUGUST
AVERAGE FOR YEAR
HEIGHT - KILOMETRES.
0
1
2
3
4
5
6
7
8
9
10
220
230
240
250
260
270
280
290
TEMPERATURE ABSOLUTE

FIG. 1.

based upon the relation between isothermal height and lapse rate height.* The first, due to Professor H. Filon, F.R.S., embodied a flexible strip carrying the lapse rate height scale and sliding in a suitably chosen equiangular spiral groove. The second form known as the "Iris" dial and patented by the writer and a colleague comprised an iris diaphragm giving a circle of varying diameter set according to ground temperature and covering a series of curves. These curves were obtained by plotting for a series of ground temperatures a table of isothermal heights corresponding to all lapse rate heights.

Such instruments give directly within about 1 per cent. the true height on about two out of three flights in England.

Improvements in Construction

The design of the altimeter is too well known to need description here, but it is worth noting that the older types of instrument gave serious errors when subjected to temperatures varying from +50°C. to −50°C., and that the lag of an altimeter may amount to as much as 300 feet after a rapid descent from, say, 2,000 feet. The chief aims in modern design are the elimination or reduction of lag and the automatic correction for temperature changes associated with height. Lag has been reduced by the redesign of the diaphragm box, the mounting of the main spring, and the reduction in amount and careful distribution of the solder on the joints. The nickel silver diaphragms should have a definite degree of hardness and the best results have been obtained with Grade A1 nickel silver rolled down to 7/6 of its finished thickness, annealed and rolled down to its final thickness in easy stages by cross rolling. Diaphragms thus produced of 2.1 inches diameter and of 0.006 or 0.007 inches thickness show in completed altimeters of 26,000 feet range an indicated lag of approximately 10 feet.

The improved method of mounting the spring is shown in Fig. 2.

The value of the changes made may be indicated by taking the lag of an old type altimeter to be of the order of 500 feet. By improved capsule construction this was reduced to 250 feet; by the selection and treatment of material, reduction was made to 75 feet, and by correct spring mounting the total lag was reduced to 10 feet.

The reduction of temperature error has been achieved by the construction of apparatus in which the conditions of pressure and temperature of the air may be simulated at will. The use of this low pressure low temperature chamber has had a marked effect on the design of almost all instruments, and some manufacturers have constructed similar plants for their own use.

In an altimeter ranged to 40,000 feet, and constructed by a maker of repute, the error at maximum height was minus 1,300 feet, although compensation had been attempted by the provision of a bimetallic strip. With the strip removed the error was plus 600 feet. By fitting to the pointer a thermostatic helix providing for a proportional negative pointer movement the error was reduced to plus 80 feet.

Experimental results show that it is better to construct the parts of a movement of a suitable metal and of such design that the minimum change takes

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* It can be shown that if H be the "isothermal height" and h the "lapse rate height" at the same pressure then the two heights are connected by the equation

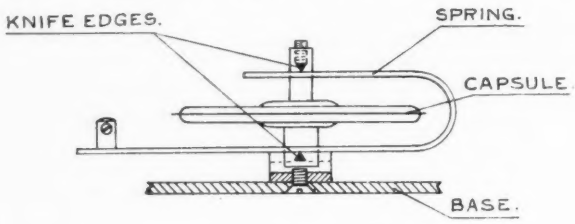
$$h = (\theta_1/\sigma)(1-\varepsilon^{-\sigma H/\theta_0}).$$

where θ_1 = ground temperature, absolute, from which the lapse rate begins.
θ_0 = constant temperature absolute of the isothermal height.
σ = lapse rate.

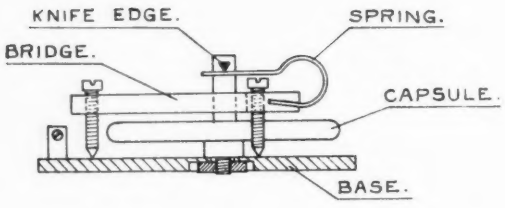
Inserting the lapse rate of 1.98° C. per 1,000 feet of lapse rate height and the value of θ_0 as 283, the formula becomes

$$h = (\theta_1/1.98)(1-\varepsilon^{-.007H}).$$

place in the mechanism itself and to provide for the variation in spring stiffness, due to temperature changes by fitting a thermostatic helix to the pointer.



MARK VII.



MARK V.

CAPSULE AND SPRING MOUNTINGS.

FIG. 2.

Typical Temperature Errors

Three instruments tested for instrumental errors due to temperature ranging from +40°C. to −40°C. gave the following maximum variation:—

Approx. height in ft.	A.	B.	C.
0	320 ft. change at zero	100 ft. change at zero	50 ft. change at zero
5000	450 ,, ,, 9 % of height	50 ,, ,, 1.0% of height	15 ,, ,, 0.33% of height
10000	600 ,, ,, 6 % ,,	126 ,, ,, 1.2% ,,	30 ,, ,, .33% ,,
15000	630 ,, ,, 4.3% ,,	820 ,, ,, 2.13% ,,	80 ,, ,, .53% ,,
20000	800 ,, ,, 4.0% ,,	550 ,, ,, 2.75% ,,	
25000	1030 ,, ,, 4.1% ,,		
30000	1225 ,, ,, 4.1% ,,		

The instruments referred to were:—

A. A foreign instrument ranged to 30,000 feet, date 1924.
B. A British instrument of conventional design ranged to 20,000 feet, date 1924.
A British experimental construction ranged to 15,000 feet, date 1925.

Fig. 3 shows the construction of a modern Mark VII. instrument.

For performance purposes a higher grade of altimeter of limited range has been devised and an example is shown in Fig. 4. This type of instrument has been found to be sensitive, accurate in indication and free from pointer vibration.

In a 2,000 feet altimeter with a once-round scale and mechanism adjusted to an even scale covering 4,000 feet, the maximum ranging error was in no case greater than 10 feet and the difference between up and down readings was only 4.5 ft.

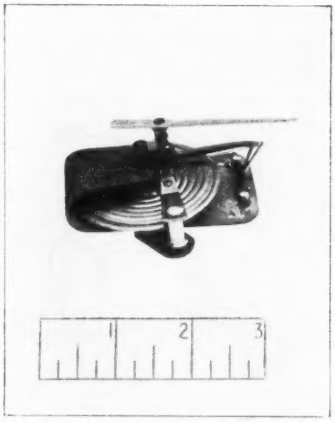


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FIG. 3.

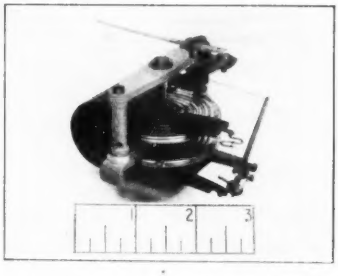

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FIG. 4.

Errors Due to Cockpit Pressure

The altimeter, as normally constructed, is provided with a case having a leak to atmosphere in order that it may measure atmospheric pressures. When mounted in an aircraft such an instrument actually measures the cockpit pressure which is subject to considerable variation from that of the surrounding atmosphere. Recent experiments have shown that this difference of pressure is sufficient to cause an error of 150 feet in an altimeter of standard pattern, installed in the normal manner. By connecting an airtight altimeter case to the static head of the air speed system, this error may be reduced to one of 30 feet.

The error is greater as the speed of the machine increases and decreases slightly as the height increases.

Air Speed Indicators

The advance in air speed measurement is substantially limited to improvements in the diaphragm and constructional details of the indicator, which enable the instrument to measure speed more accurately and to be far less susceptible to ageing and temperature errors. A point of interest is that British practice of using the low power but accurate pitot static head combined with a sensitive high grade indicator, instead of the more powerful head of the Venturi type in combination with a robust indicator common in American and Continental practice, is finding more favour in the United States and in France. A modified

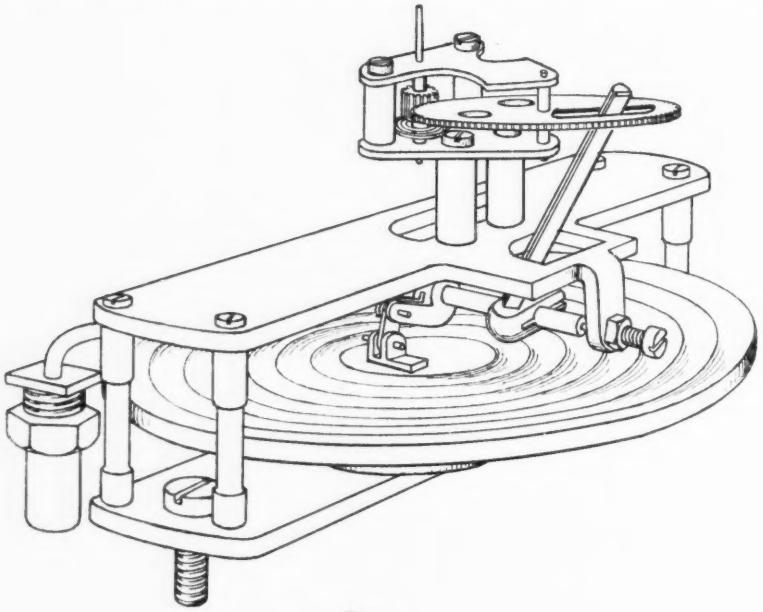

FIG. 5.

type of pitot head has been evolved to overcome dust trouble in tropical countries and also to combat the obstructive visits of that Indian insect which seeks to partake of free air travel by secreting itself in the pitot tube.

Before proceeding with the description of the developments in the indicating portion of the instrument, it is interesting to call to mind that the pitot static type of head at a speed of 120 miles per hour, provides for the actuation of a manometer, about one-twelfth of the pressure given by a double Venturi.

The nature of the achievement of our instrument makers in producing a robust, steady air speed indicator with an accuracy of from one to one and a half miles per hour over a speed range of 40 to 170 miles per hour will be appreciated. Instruments of this kind have been tested under a range of temperature of $+40°C.$ to $-30°C.$ and found to possess an error of within one mile per hour. Such an instrument has been made by S. Smith and Sons, Cricklewood.

Applying the experience gained in altimetry and extending the experimentation, instruments have been constructed at Farnborough reading from 40 to 320 m.p.h., which exhibit an error of from one to one and a half miles per hour under the temperature range mentioned above. The substitution of iron for brass in the construction of the bosses on the diaphragm has materially assisted in reducing temperature errors.

Due perhaps to some peculiarity in our national character, the British instrument maker is denied the advantage enjoyed by the American and Continental manufacturers, for as the range of an instrument is increased he is forced to extend the length of his scale, with the result that a foreign instrument of well-known make possesses a scale length of five inches, whereas the corresponding British indicator has a scale of approximately 16 inches in length. The great range of temperature that aircraft instruments are forced to withstand has caused the virtual elimination of rubber and fabric diaphragms in air speed indicators, except for special work in temperate climates. The ageing of rubber diaphragms is a well-known source of trouble and it is not uncommon

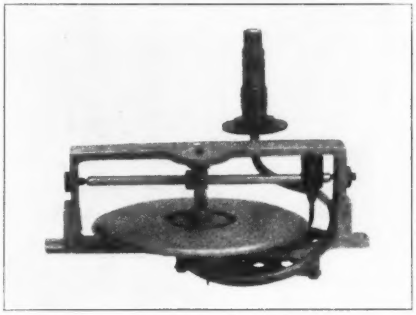

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FIG. 6.

with fabric diaphragm indicators to find an error of about 18 m.p.h. at a temperature of $-30°C$. The metal diaphragm instrument has, however, successfully withstood flights in an atmospheric temperature of $-56°C$. in England and exposure to a temperature of $+60°C$. in Iraq.

Fig. 5 shows the mechanism of the Smith metal diaphragm air speed indicator, the special features being the provision of a bimetallic long arm, the balance of the mechanism and the special form of the corrugations in the diaphragm. At a temperature of $-30°C$., and when the pointer was indicating speeds from 90 to 160 m.p.h., the total error was of the order of one half mile per hour. Figs. 6 and 7 show the Royal Aircraft Establishment 40-320 m.p.h. air speed indicator, the special features of which are the provision of two dissimilar diaphragms, the weaker of which is supported on a fixed shroud during the period of high pressure on the capsule.

To remove the recurrent trouble due to leakage, the rubber joint between the lengths of aluminium tubing connecting the pitot head to the indicator has been replaced by an all-metal joint, the more recent form of which incorporates a non-metallic nipple forming the jointing medium.

For special purposes the anemometer type of air speed indicator is still used and an instrument of recent design, due to H. L. Stevens and D. A. Jones for use in aerodynamic research at the Royal Aircraft Establishment, is shown in Fig. 8. This consists of a windmill suspended below the aeroplane in the manner

of a suspended static head which, through reduction gearing, operates electrical contacts. The circuit so made leads by a cable running up the suspension cable to a solenoid which in turn operates a counter. The number of contacts is checked by a stop watch during a given time interval. The instrument is used for measuring the air speed during slow speed glides.

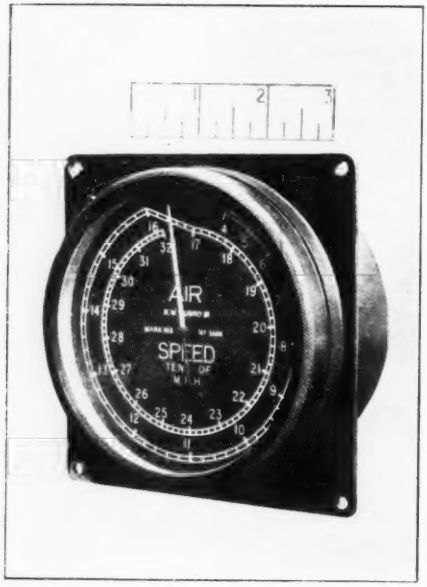

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FIG. 7.

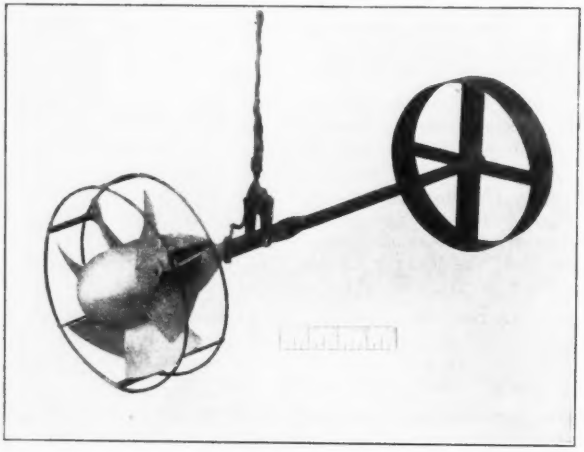

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FIG 8.

Portable Air Speed Calibrator

To facilitate the easy checking of air speed indicators a small replica of the float type calibrator used in test houses has been constructed. Another form of calibrator of the water column type is also used and is shown in Fig. 9.

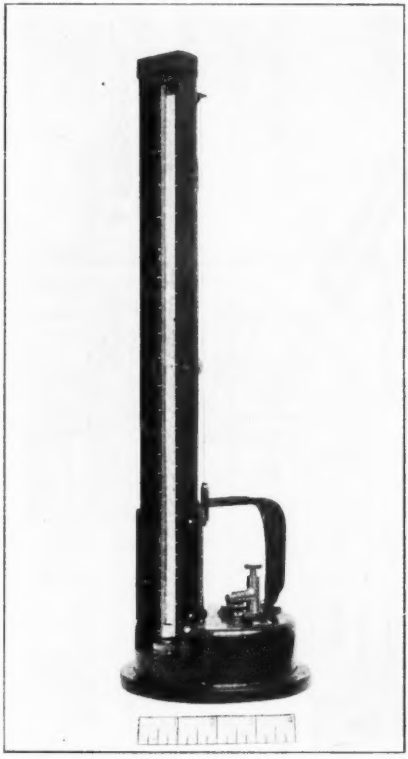

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FIG. 9.

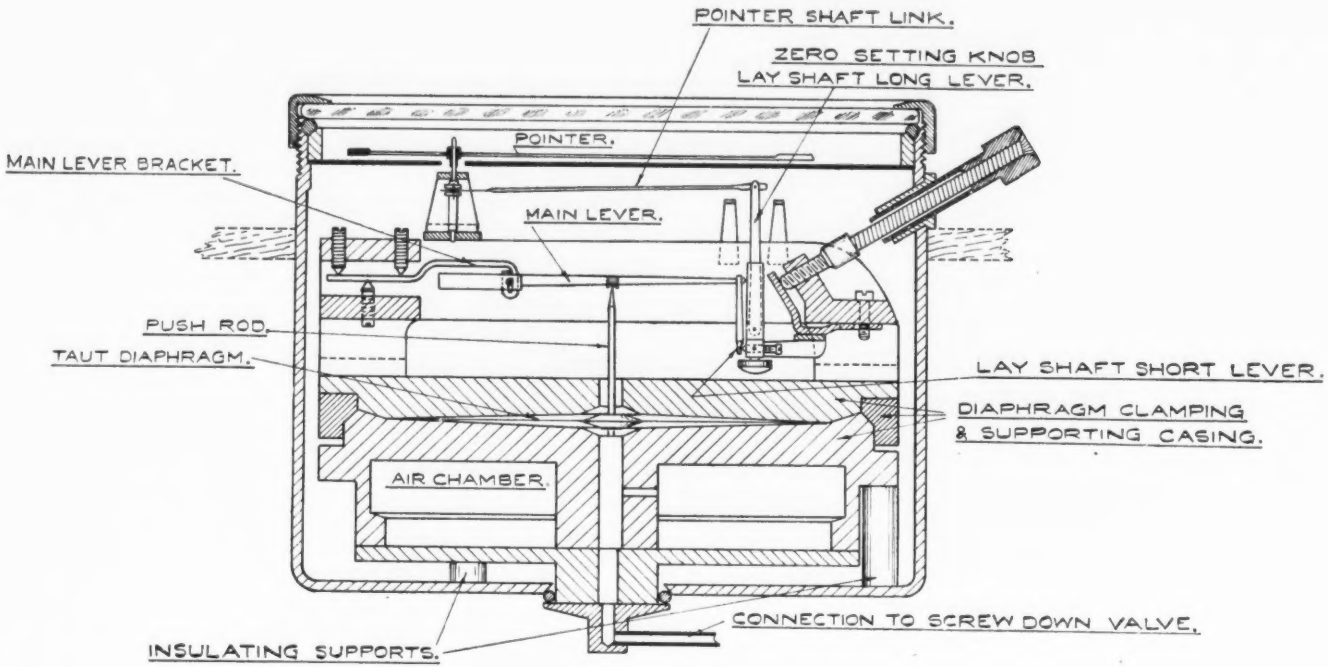
STATOSCOPES AND CLIMB METERS, HOT WIRE RATE OF DESCENT METERS

Statoscopes

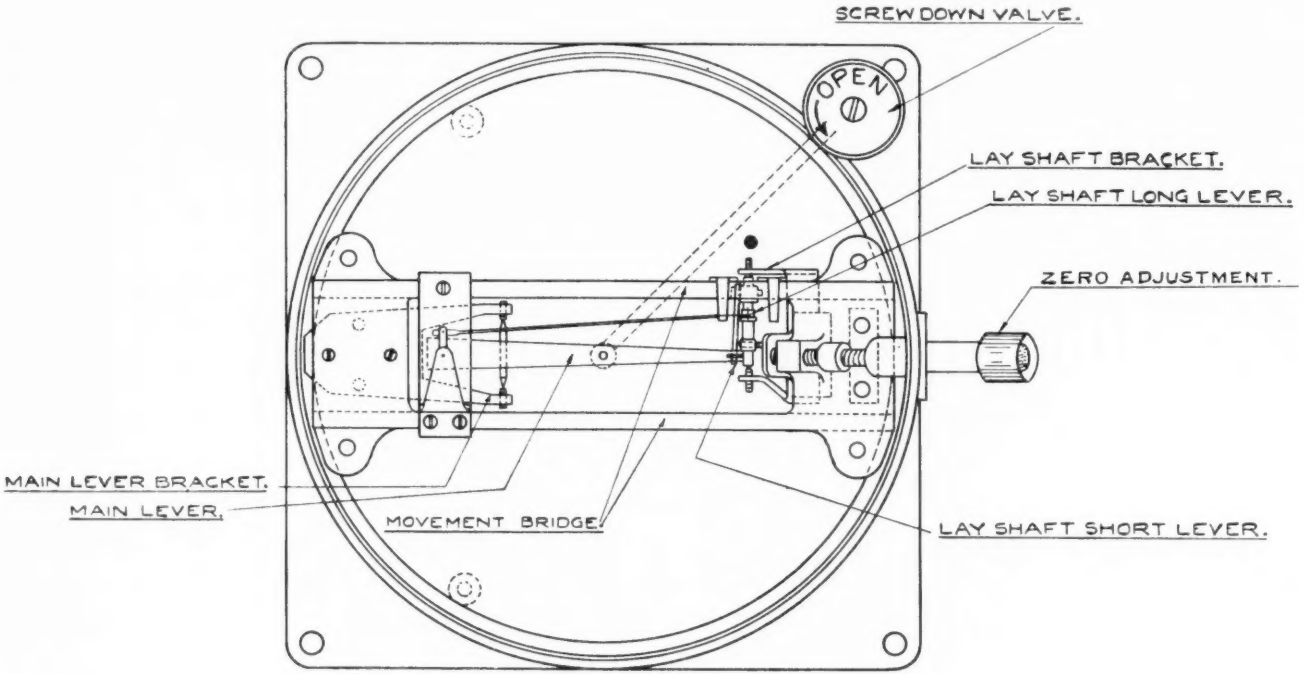
The usual breaking bubble type of statoscope is somewhat sluggish and irregular in action and efforts have been made in this and other countries to produce a more positive and reliable instrument of a mechanical nature. One such instrument of American design is described as capable of detecting differences of altitude of approximately 5 feet.*

An instrument constructed at Farnborough by Mr. Gregory is shown in Figs. 10 and 11. The statoscope is put into operation by closing a screw-down valve when the altitude is reached at which it is desired to maintain level flying. The closing of the valve seals a quantity of air in a chamber covered by a

* *Journal of the Optical Society of America and Review of Scientific Instruments*, March, 1926.



SECTIONAL ELEVATION.



R.A.E. ALL-METAL STATOSCOPE.

PART PLAN.

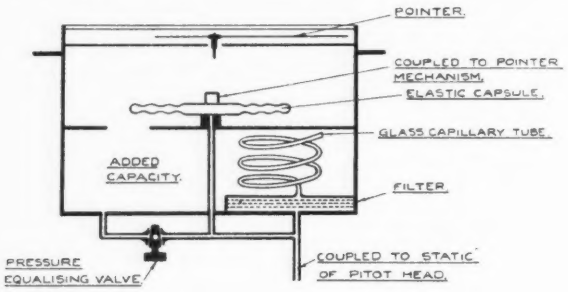
FIGS. 10 & 11.

tightened duralumin diaphragm 0.0015 inches thick and 3.6 inches diameter. Change of altitude causes a displacement of the diaphragm, the movements of which are communicated through a lever system of high magnification to a light pointer operating over an arc of approximately 45° on either side of a central zero. The maximum useful movement of the diaphragm is of the order of ±0.02 inches, while the maximum possible movement is ±0.03 inches, after which the diaphragm is rigidly supported by its shrouding case.

The complete unit is air-jacketed and contained in a light aluminium case. The scale is open and can be read to within 5 feet.

Climb Meters

Instruments for measuring the rate of rise or descent are necessary on airships, but they have not hitherto found much favour in aeroplane work except for special test purposes, due no doubt to the large errors they possess and the difficulty in detecting low rates of climb or changes in the rate of climb, without the introduction of considerable lag. The designs of the older instruments of this type were based on the use of a liquid manometer which, of course, is subject to considerable errors due to acceleration. Later attempts have been made to substitute capsule manometers for the liquid element, but as will be



R A E RATE OF CLIMB INDICATOR
(SELF CONTAINED PATTERN)

FIG. 12.

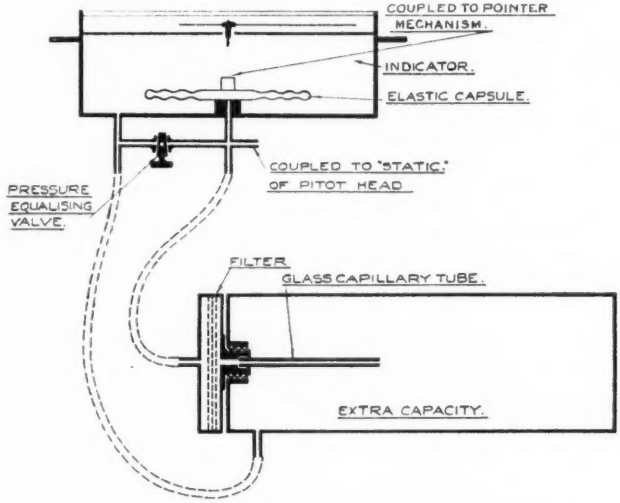
seen from the following theoretical treatment of the subject such manometers must exhibit one of two characteristics, both undesirable, a pronounced lag in reaching the final reading or a pronounced insensitivity to low rates of change. Useful compromises have been developed in this country and in America, and in 1920 a rate of climb meter for airships was constructed, using the rubber diaphragm of the Darwin turn indicator. Metal diaphragms have replaced the rubber and fabric diaphragms, but so far this has caused a drop in the sensitivity of the instruments.

Two examples of the all-metal mechanical type are shown in Figs. 12 and 13. The former shows the usual type of self-contained instrument having a capillary leak to the capacity. In this case the capillary is 17 inches in length. As the instrument is susceptible to small changes of pressure the case is coupled to the " static " tube of the pitot static head. The latter figure shows an instrument in which the capacity is separate from the indicator, and so arranged that the leak may be varied by fitting capillary tubes of varying bore as required.

Before describing the most recent work on this type of instrument it is advisable to present the theoretical aspect of the problems underlying the design.

In this type of instrument the indication is obtained from the movement of a diaphragm subjected to static or atmospheric pressure on one side and on the other to the pressure in a chamber of air capacity connected through a capillary tube to static or atmospheric pressure.

Let P = pressure of the surrounding atmosphere.
P_1 = pressure of air in the chamber.
P_2 = pressure of air in the capillary tube.
p = the pressure difference $P_1 - P$.
ρ = density of surrounding atmosphere.
ρ_1 = density of air in the chamber.
ρ_2 = density of air in the capillary tube.
V = volume of chamber.
m = mass of air in the chamber.
l = length of capillary tube.
r = radius of capillary tube.
η = viscosity of the air in the capillary tube.



R.A.E. TRIPLE RANGE RATE OF CLIMB INDICATOR.
(WITH EXTRA CAPICITY.)

FIG. 13.

Assuming isothermal conditions in the chamber, and neglecting quantities of the second order, it can be shown that

$$p = -(1/K)(d \log P/dt) - ce^{-\{kP/(1+\epsilon)\}t} \quad . \quad . \quad . \quad (1)$$

where $K = \eta r^4/8l\eta V$ and $\epsilon = aP_1/V$ where $a = dV/dp$

and that in the ultimate steady reading of the instrument

$$p = -(1/K)(d \log P/dt) \quad . \quad . \quad . \quad . \quad (2)$$

The quantity involves the constructional detail of the instrument and for good design should be small. For example, the change in volume of the chamber for a given change in atmospheric pressure should be small. During a reading variations of P_1 are small and in any actual instrument may be assumed constant.

The exponential part of the equation gives a measure of the time lag T of the instrument. If the instrument is indicating a steady condition and this condition is suddenly changed, the time lag is defined as the time taken for the error in reading to reach $1/e$ of its initial value and is given by

$$T=(1+\epsilon)/KP$$

Limitations of the Diaphragm Capacity Leak Type

The important considerations in the design of a rate of climb or descent meter are evidently time lag and insensitivity, the latter being defined as the lowest indication of the instrument that can be read. Putting $R=dH/dt$ for the ultimate reading of an instrument and ΔR the lowest readable indication

$$\Delta R=-(P/g\rho)\,\Delta d \log P/dt=(P_0/g\rho_0)\,K\Delta p \quad . \quad . \quad . \quad (3)$$

where Δp is the smallest observable pressure difference and P_0 and ρ_0 represent atmospheric pressure and density at ground level.

If Δp is a fixed quantity it follows that for any value of P

$$T\,.\,\Delta R=\text{constant}\times(1+\epsilon) \quad . \quad . \quad . \quad . \quad (4)$$

where the constant $=\Delta p/g\rho$ and the term $\epsilon=P_1 d \log V/dp$.

For a given chamber sealed by a diaphragm it is possible to evaluate ϵ from the observed dimensions of the chamber and the movement of the diaphragm.

A series of values of ΔR and T have been calculated for different values of K and for a diaphragm and movement for which $\Delta p=148$ dynes per sq. cm. or 1.5 mm. of water. Curves, shown in Fig. 14, have been plotted connecting these values of T and ΔR for the two cases $\epsilon=0$ and $\epsilon=0.1$. These values of ϵ may be taken as the limiting values governed by the values of V, which may be conveniently used. The substantial coincidence of these curves indicates that the only factor materially affecting the design of such an instrument apart from the diaphragm and movement is the ratio of the flow through the capillary for unit pressure difference to the volume of the chamber.

$$\text{This ratio}=\pi r^4/8l\eta V_0=K$$

In designing an instrument, therefore, it is necessary first to decide upon a particular diaphragm and movement to obtain a minimum value of Δp. By inspection of the $T\Delta R$ curve for this diaphragm and movement it is then possible to select a value of the ratio of the chamber volume to leak which will

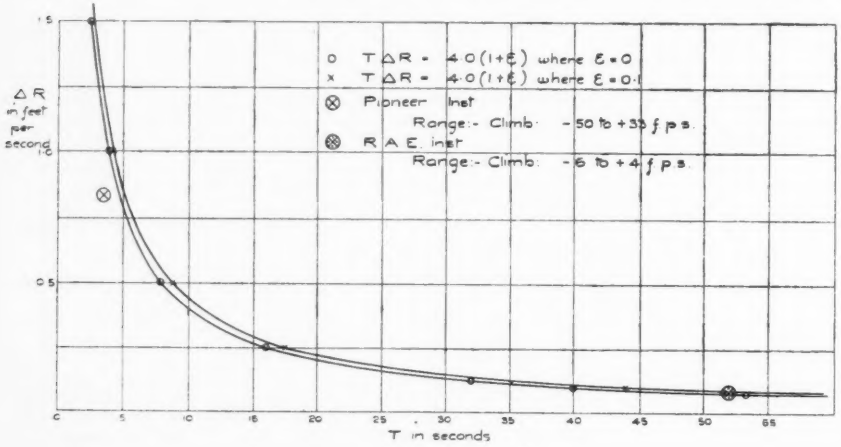
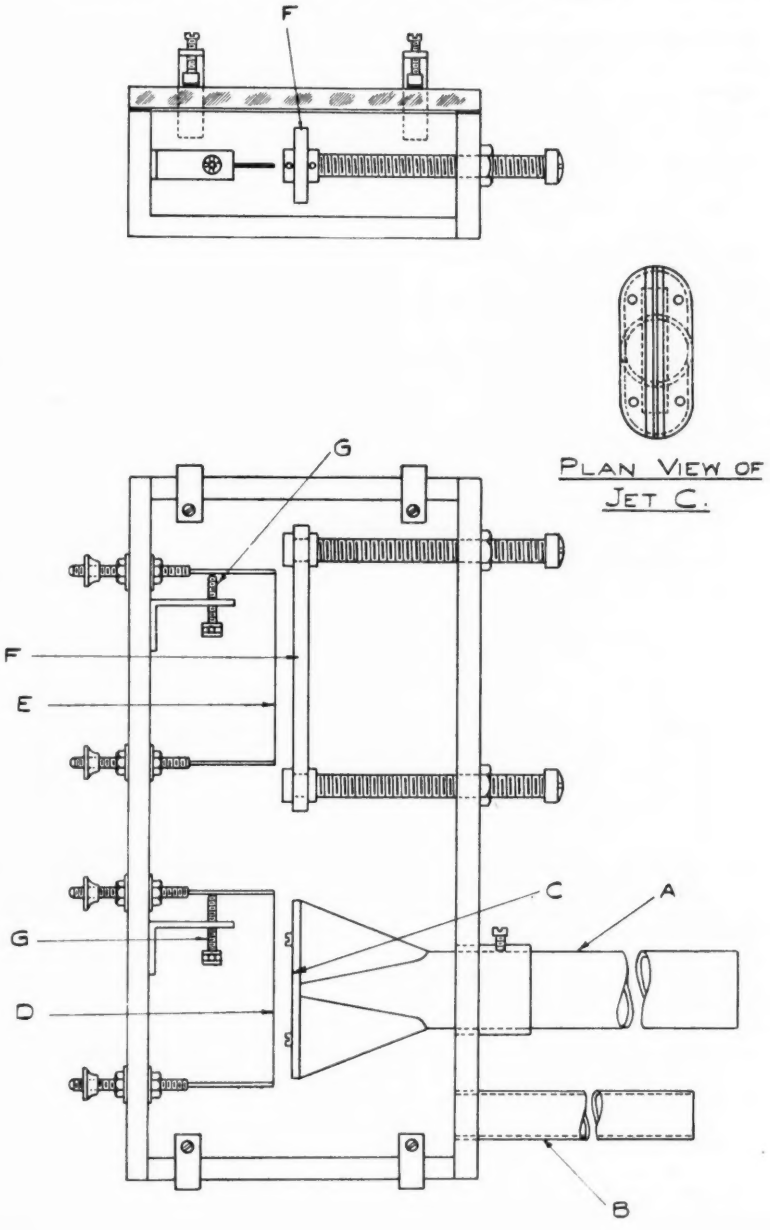


FIG. 14.



HOT WIRE RATE OF DESCENT INDICATOR.

FIG. 15.

give the compromise between time lag and insensitivity best suited to the object in view.

Fig. 14 shows a comparison between an American and British instrument, the values of Δp being 110 dynes per sq. cm. and 158 dynes per sq. cm. respectively. The wide difference between the climb ranges that the instruments are used for is noted on Fig. 14, but it is obvious from the close relation of the characteristics of the diaphragms and movements, that either instrument could be modified to fill the requirements of the other by altering its capillary leak.

Hot Wire Rate of Descent Meter

This instrument was developed at the Royal Aircraft Establishment by Mr. F. W. Meredith and Mr. G. W. H. Gardner to provide a means of measuring the instantaneous rate of descent of aeroplanes in disturbed motion. Clearly the old type of capacity and leak instrument depending on a pressure measuring diaphragm was useless for this purpose, since no diaphragm and movement

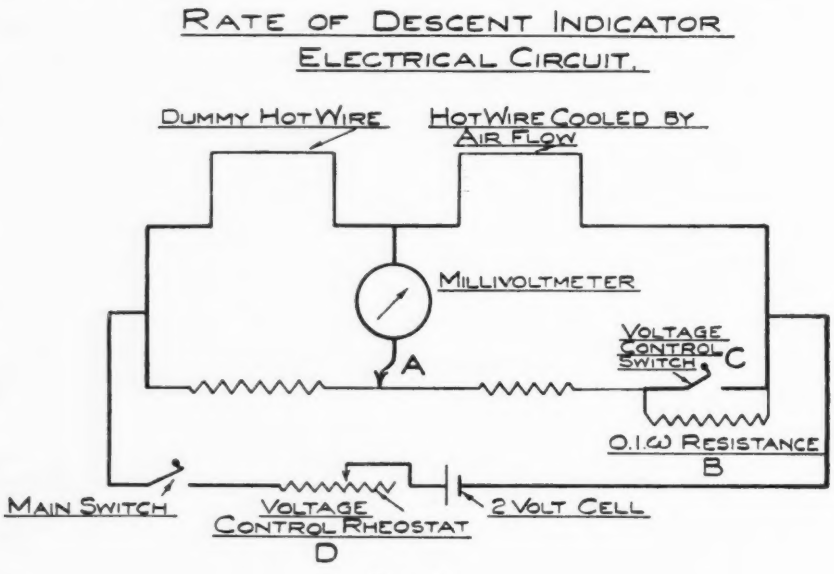


FIG. 16.

was sensitive enough to measure the small pressures available if the leak were made large enough to reduce the capacity lag to reasonable proportions.

The hot wire instrument depends also on the measurement of the flow into a capacity chamber, but the flow is measured by the change in resistance of a hot platinum wire placed across the stream and so the restriction can be reduced to such an extent as to render the capacity lag negligible. There is still the heat capacity lag, but provided the diameter of the hot wire is small enough this lag is only of the order of half a second. The construction of the instrument is shown in Fig. 15. The pipe A is connected to a static head, preferably a suspended head, and pipe B is connected to a thermally insulated capacity chamber. Thus, when the aeroplane is descending air passes into the box through the jet C and impinges on the platinum wire D and then passes out

of the box by the pipe B to the chamber. E is a second wire placed in the box so as to be subjected to contact with air at the same temperature and pressure as that in contact with the first wire. These two wires form adjacent arms of a Wheatstone bridge which is shown diagrammatically in Fig. 16. F is an adjustable metal plate provided to equalise, when properly adjusted, the rate of heat dissipation from the two wires when no air is passing through the jet so that the zero of the bridge is not disturbed by changing the pressure of the air in the box. Screws G are provided for tensioning the two wires.

Figure 16 shows the electrical connections. The potentiometer slide A is used to balance the bridge when the air flow is shut off by a tap. The resistance B is placed in circuit by opening the switch C so as to give a datum reading on the millivoltmeter as a check on the voltage across the bridge. This voltage can then be adjusted by the rheostat D. The switch C is then closed and when the tap in the pipe line is opened the instrument is ready for use. This tap is arranged to connect the capacity direct to the static head when in the " off " position.

The rate of descent indication is a function of the galvanometer indication. In the actual instrument constructed the rate of descent can be read conveniently to about one foot per second, equivalent to one millivolt on the galvanometer. The lag is 0.6 seconds and agrees with that predicted theoretically for the thermal capacity lag.

Corrections are made to the calibration curve for the observed temperatures of the outside air and the chamber when accurate quantitative results are required. Without these corrections the instrument serves as a convenient detector of disturbances from a steady rate of descent.

Diaphragms and Pressure Capsules

The design of all the pressure measuring instruments used on aircraft involves assumptions regarding the behaviour of the capsules, whether disc or tubular, which sustain the pressures to be measured. Hitherto no technically useful theory of the action of pressure capsules has been available and progress has therefore been based on empirical methods. The problem is under treatment by Dr. A. A. Griffith, of the Royal Aircraft Establishment, who has investigated the behaviour of capsules made of materials whose stress-strain relations are such as to permit the application of the mathematical theory of elasticity to the consequent exclusion of capsules made of very flexible or extensible materials such as rubber and fabric. It has been mentioned previously that the latter materials are finding less favour in general aircraft instruments. Since the elastic moduli of the materials, whose properties comply with the conditions named above, are very large compared with the pressure differences to be measured, capsules made of such materials must of necessity be thin, and the theory of pressure capsules becomes therefore an extension of the theory of thin elastic shells, such extension being called for by the fact that the displacements of pressure capsules are not sufficiently small to be considered as infinitesimal.

It is shown in works on the theory of elasticity that thin shells are subject to two distinct kinds of deformation, (1) extensional, involving the extension of the neutral surface, (2) inextensional, in which such extension of the neutral surface does not occur. In thin capsules of a given thickness the strain energy of and the maximum stresses set up by a given proportional deformation of the extensional kind are much greater than in the case of a corresponding inextensional deformation. This indicates that the inextensional type of deformation is more suitable for pressure capsules, since a greater flexibility can be obtained and also a greater permissible deflection without overstraining the material. It has been shown by Jellett* that no closed shell can be deformed to a finite extent

* J. H. Jellett, *Dublin Trans. R. Irish Acad.*, Vol. 22 (1855).

in a purely inextensional manner. It is not possible, therefore to avoid in capsules the existence of extensional strains, and the problem becomes that of reducing as much as possible the extensional strains and strain energy. Designs obtained empirically have in fact tended towards this achievement. Jellett's theorem is restricted to the conditions of (1) a closed shell, and (2) a finite displacement. The first condition implies that open shells may be devised of such shape that they can undergo finite inextensional deformations with the restriction, of course, that closure will involve extension strains. If such a shell can exhibit in action a preponderance of inextensional strain, and the extensional strains can be limited to small and well defined areas, then the capsule will exhibit in the main definable characteristics, but the small locality or localities of extensional strain will suffer, due to concentration of stress, and will ultimately rupture. This indicates restriction in the range of design.

The second condition of Jellett's theorem implies that forms of capsules can be obtained such that the strains are inextensional for infinitesimal displacements, or as a corollary that the extensional strains are proportional to some power of the displacement higher than the first. It follows that there must be a finite range of displacement in which the effect of extensional strains is small. This is the method of small displacements so frequently used in current designs, and in the usual corrugated disc the extensional strains which accompany finite deformations are small and are concentrated at the flanks of the corrugations. The depth of the corrugations should not, however, be uniform as commonly designed, but should be greatest in the neighbourhood of the annular region where the slope of the deflected plate is greatest and should diminish to zero at the centre and the outer edge where the slope is zero. In discussing the behaviour of pressure capsules, it is necessary to take cognisance of the initial stresses in the material of which the capsule is formed, since the equilibrium configuration of the capsule is not merely caused by the applied forces and the stresses induced by them, but also by the variation in the initial strain energy. The technical importance of these initial stresses is largely due to the fact that all existing processes for the manufacture of capsules involve the introduction of initial stresses into the material and the magnitude and distribution of these stresses depend on the nature of the manufacturing processes. Experience with pressure capsules appears to indicate that their temperature coefficients are in many cases widely different from the temperature coefficients of the relevant moduli of elasticity. The cause of this is at present obscure, but may be due to cold working, or alternatively to the fact that all technical capsule materials suffer to a greater or less extent from defective elasticity.

The problem of the complete flat disc without control spring has been attacked by a method of successive approximation which is theoretically capable of giving the solution to any required order of accuracy. A first application of the method yields the result previously inferred by Prescott* for the general case of plates deformed by pressure, viz., that the classical theory of the bending of thin plates is valid only if the square of the central deflection is small compared with the square of the thickness, no matter how small the latter may be in comparison with the radius.

A second application shows further that the results of the first application are valid to the order of approximation required in practice, provided that the deflection does not exceed about eight times the thickness. The method of successive approximations has been employed for the reason that the theory given in text books of elasticity is restricted to infinitesimal displacements, and the attempt to achieve a higher order of approximations by applying the theory to cases of finite displacements leads to the introduction of non-linear differential equations which cannot at present be solved exactly.

* The Equations of Equilibrium of an Elastic Plate Under Normal Pressure, *Phil. Mag.*, January, 1922, p. 97.

SUMMARY OF RESULTS

List of Symbols

r = radius at any point of the disc.
R = radius of outer edge.
t = thickness of disc.
w = deflection at any point.
W = deflection at centre.
σ = Poisson's ratio of the material.
F = plate modulus of the material $= E/(1-\sigma^2)$ where E is Young's modulus.
e = maximum permissible difference of the principal extensions to which the material is subjected.
e_0 = extension due to uniform initial tension.
p = pressure difference applied to the disc.

Case I.

Outer edge of disc completely fixed. Initial radial extension e_0.

$$w=(W/R^4)(R^2-r^2)^2\left[1+(1+\sigma/3)(e_0r^2/t^2)+(1+\sigma/360)(w^2r^2/t^2R^8)\{40R^6+(1-\sigma)(76R^6-45R^4r^2+14R^2r^4-2r^6)\}\right] \quad . \quad . \quad . \quad . \quad . \quad (5)$$

$$p=(16/3)(Ft^3W/R^4)\{1+(5/6)(1+\sigma/6)e_0(R^2/t^2)+\{(1+\sigma)(173-73\sigma)/360\}(W^2/t^2)\} \quad . \quad . \quad . \quad (6)$$

$$e-e_0=(4Wt/R^2)\{1+[(1+\sigma)/3]e_0(R^2/t^2)+W/12t+[(1+\sigma)(83-43\sigma)/360](W^2/t^2)\} \quad . \quad . \quad . \quad (7)$$

Case II.

Outer edge of the disc fixed so that rotation of the elements is prevented while radial displacement is unconstrained. This condition occurs when two similar discs are united at their outer edges so as to form a complete capsule.

$$w=(W/R^4)(R^2-r^2)^2\{1+[(1-\sigma^2)/360](W^2r^2/t^2R^8)(76R^6-45R^4r^2+14R^2r^4-2r^6)\} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

$$p=(16/3)(Ft^3W/R^4)\{1+[\{73(1-\sigma^2)\}/360](W^2/t^2)\} \quad . \quad (9)$$

$$e=(4Wt/R^2)\{1+(1-\sigma^2)(W/12t+\{43/360\}\{W^2/t^2\})\} \quad . \quad (10)$$

For technical purposes the above formula are sufficiently accurate provided that the central deflection is not more than eight times the thickness. In Case I. there is the further limitation that the initial extension e_0 must not be large compared with t^2/R^2.

In Case II. and also in Case I., provided that $e_0=0$, the forms of the equations for p and e are such that the variables

$$(p/e^2F)(W/R\sqrt{e})(t/R\sqrt{e})$$

can all be expressed as functions of σ and the single parameter W/t. For most practical purposes the variation with σ may be neglected, a mean value of $\sigma=\frac{1}{3}$ being adopted. It is then possible in each of the two cases considered to construct two curves having values of p/e^2F as abscissæ and values of $W/R\sqrt{e}$ and $t/R\sqrt{e}$ respectively as ordinates.

These curves plotted on logarithmic paper are shown in Fig. 17. The curves cover the range $p/e^2F=0.01$ to $p/e^2F=1.00$, which is practically the full range of the validity of the equations on which they are based. The dotted lines show for comparison the values calculated from the inextensional or first order solution given in elasticity text books.

When the relevant properties of the material are known, these curves furnish all the information for the design of flat disc capsules.

Moreover, since the function of the corrugations in corrugated disc capsules is merely to minimise the effect of the extensional deformation, it follows that for

any value of p/e^2F the values of $W/R\sqrt{e}$ and $t/R\sqrt{e}$ respectively, for any corrugated disc must lie between the corresponding values given by the dotted lines (in calculating which the stretching was entirely neglected) and the values given by the full lines (in which stretching is taken into account).

It will be seen that the curves for $t/R\sqrt{e}$ are in close proximity over the whole range, indicating that the thickness for any complete disc is determined mainly by the value of p/e^2F and is little affected by the introduction of corrugations. The curves for $W/R\sqrt{e}$, on the other hand, deviate more and more

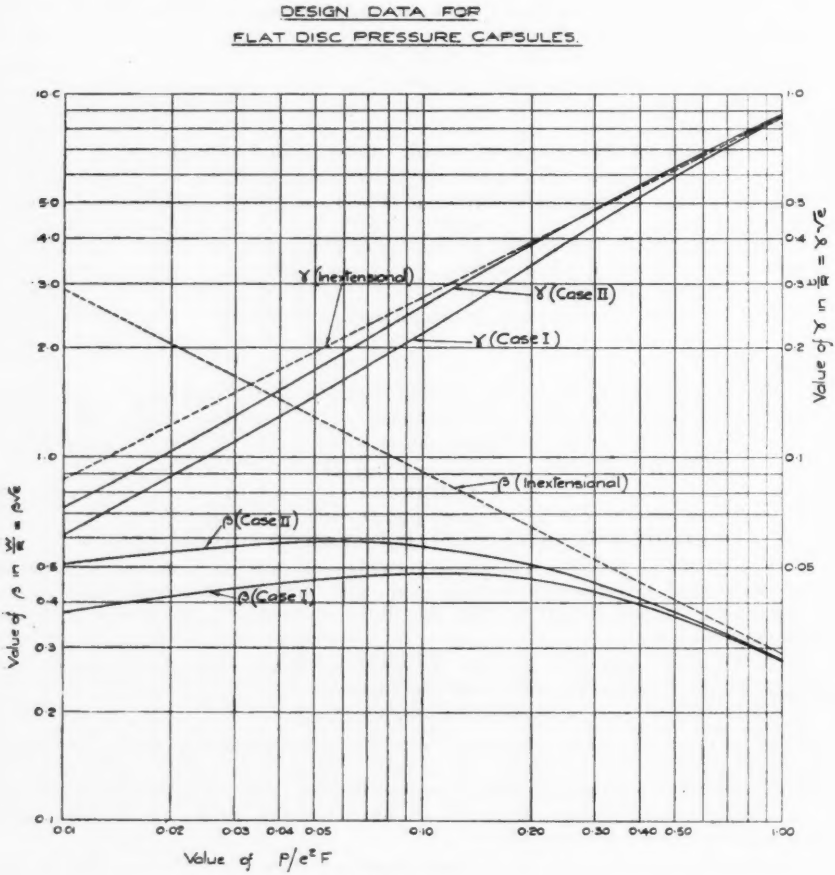


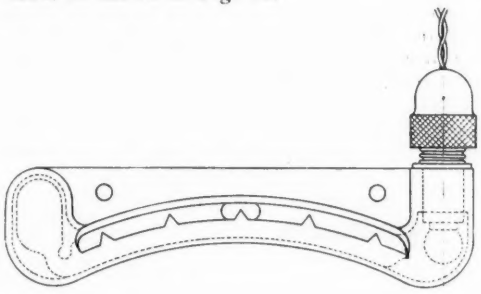
FIG. 17.

from the dotted line as p/e^2F diminishes. The smaller the value of the latter quantity, therefore, the greater is the potential increase in safe deflection which is obtainable by corrugating. It will be seen that for discs made of a given material and having a given diameter there is a particular thickness which makes the safe deflection a maximum. This thickness has the value of 0.240 $R\sqrt{e}$ in Case I. and 0.191 $R\sqrt{e}$ in Case II.

INCLINOMETERS

Bubble Type

This instrument has been improved to meet the serious trouble met with in hot climates, where the old type of liquid-filled instrument burst through the expansion of the liquid. The improvement consists in providing a liquid trap at one end of the tube, as shown in Fig. 18.



LUMINOUS BUBBLE INCLINOMETER

FIG. 18.

GYROSCOPIC TURNING INDICATORS

The following instruments have been previously described and it is not proposed to deal with them in this paper:—R.A.E. (air-driven), Reid Control Indicator (air-driven), and the Mark IV. electric type of British origin, the Sperry air-driven and electric types, American, and the Drexler of German origin.

Two instruments, one British and one German are, however, of sufficiently recent introduction to warrant special comment.

The Schilovsky-Cooke electrically-driven gyro turning indicator is shown in Figs 19 and 20. It comprises a lateral inclinometer and a turning indicator, both

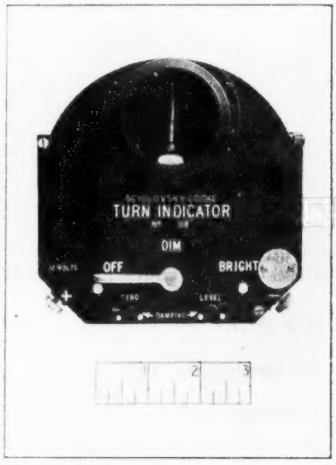


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FIG. 19.

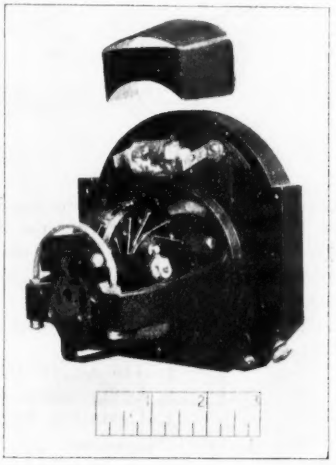

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FIG. 20.

contained in the same case, but quite independent of each other in action. Indication is by means of coloured screens operating in front of an electric lamp. The lateral inclinometer is merely a pendulum having an air damping cylinder, the leak from which is adjustable.

The turning indicator consists of a small direct current electric motor forming the rotor of the gyroscope rotating about the axis set athwartships in the aeroplane. The rotor is carried in a pivoted frame gravitationally controlled and supported on knife edges arranged at right angles to the rotor axis in the manner common to turning indicators. A movement of the aeroplane in azimuth causes the gyroscope frame to tilt about the fore and aft axis, and this movement is indicated to the pilot by means of the coloured screen secured to the frame, a red light being shown for a port turn and a green light for a starboard turn. In a correctly banked turn, the bubble mark on the inclinometer will of course

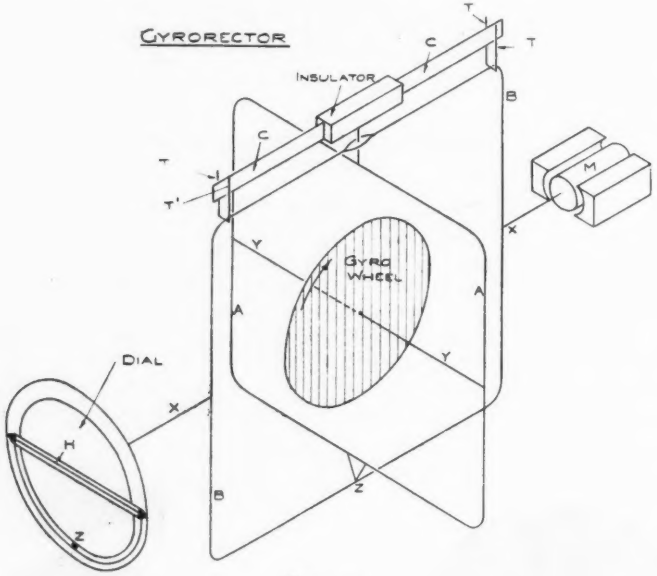


FIG. 21.

remain central with respect to the case of the instrument, while the colour screen and the marked pointer thereon will move in the direction of the turn. In a pure sideslip the bubble mark and the gravity controlled gyro pointer remain in the same position relative to each other, while the case, of course, follows the movement of the aircraft.

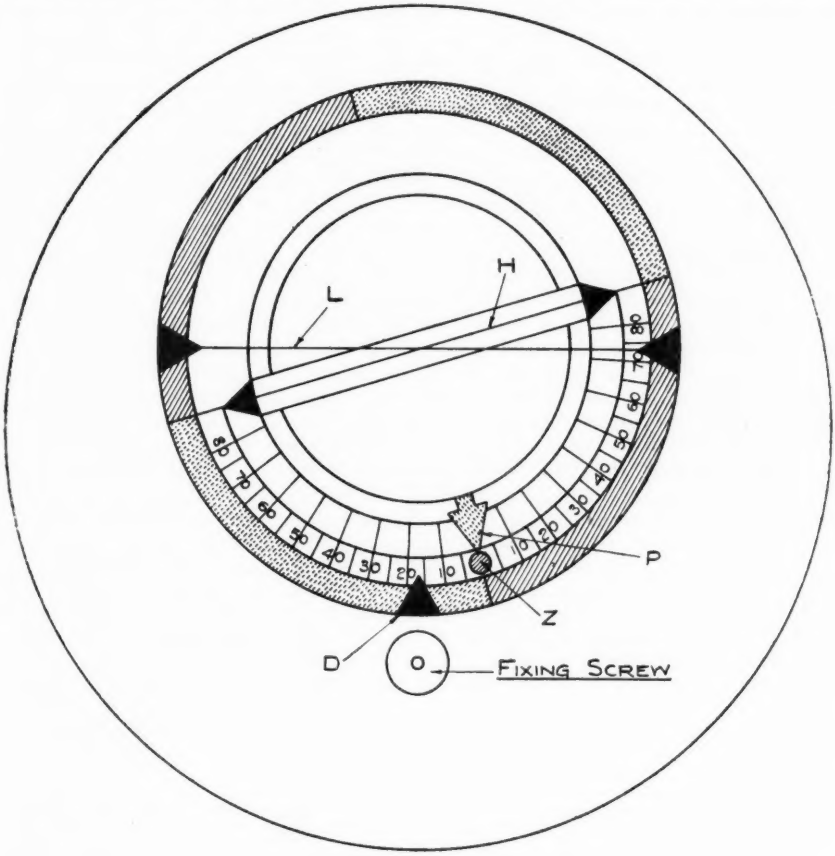
The German instrument—the Gyrorector—is a device for indicating to the pilot:—

1. Transverse inclination of the aeroplane.
2. Longitudinal inclination.
3. Deviation from the straight course.

The design is ingenious and makes a useful contribution not only to the art of flying in the absence of a visible horizontal, but also to the art of instrument design. The instrument comprises three distinct and independently working devices:—

(*a*) A gyroscopic pendulum.
(*b*) A free pendulum.
(*c*) A liquid level for indicating fore and aft inclination.

The gyroscopic pendulum is a gyro wheel driven by three-phase alternating current at a speed of about 18,000 r.p.m. and freely mounted about the azimuth and roll axes. The rotor axis Y–Y, shown diagrammatically in Fig. 21, is placed athwartships and is carried in a gymbal ring A, pivoted about the vertical axis Z–Z in a second ring B, which is in turn pivotally mounted in the instru-



GYRORECTOR DIAL.

FIG. 22.

ment case about the longitudinal axis X – X. The inner ring A carries two spring contact blades CC′ which act against contacts TT′ carried by the outer ring BB. These contacts form a reversing switch for controlling the motor M, which is geared to the ring B. The latter is made pendulous so that when displaced from the vertical a gravitational torque is produced about the axis XX, which causes azimuth precession of the gyroscope. This precession, through the action of the reversing switch, introduces an opposing torque from the motor M, which precesses the gyroscope till the switch is open again. An oscillation in azimuth results and each time the contact is made a slight torque is produced about the vertical axis ZZ by the deflection of the spring blades CC′. This torque causes the gyroscope to precess slowly about the axis XX until the azimuth oscillation is damped out in consequence of the return of the ring B to the vertical. On a turn this azimuth oscillation will occur if the precession, due to centrifugal force acting on the unbalanced mass, is not equal to the rate of turn of the aeroplane. This causes a movement about the axis XX until the torque, due to the combined gravitational force and centrifugal force, gives rise to a rate of precession in azimuth equal to the rate of turn of the aeroplane.

Since the torque producing precession is equal to the product of the angular momentum of the gyroscope and the angular velocity of precession, and since the angular velocity of the turn is equal to the speed of the machine divided by the radius of turn, it follows that for a certain ratio between the rotor speed and machine speed the pendulum may be adjusted so that the system will balance with the plane of the ring B vertical, whatever may be the radius of the turn of the aircraft.

So constructed the gyroscope will erect towards the vertical under all conditions of flight so long as the ratio between the speed of the rotor and the speed of the machine is correct. Deviation from this ratio will result in the deviation of the ring from the vertical by a fraction of the angle of bank, but this would not, under the ordinary conditions of usage of this instrument, be apparent.

A dial, Fig. 22, is rigidly attached to the ring B and lies in a plane perpendicular to the axis X – X. This dial is marked with an artificial horizon line H and zero mark Z, the lower half being graduated at intervals of 5 degrees, and the quadrant coloured red and green to indicate port and starboard. A simple pendulum oscillates in the plane of the dial and carries a pointer P indicating on the dial. The pendulum, which serves as an ordinary inclinometer, indicating the apparent vertical is, of course, quite independent of the gyro pendulum. The combined instruments are mounted in a light metal case which is spring supported and pivoted about a horizontal axis set athwartships. The dial cover glass is rigidly secured to the case and is marked with a transverse line L and arrow head D. The line L is thus always parallel to the transverse axis of the machine. A spirit level serving as a fore and aft inclinometer is attached to one of the casing supports.

Examples of the indication of the instrument are shown in Fig. 23. These will be clearly understood if the black line indicating the artificial horizon is read horizontally. The total weight of the apparatus is 35 lbs.

THERMOMETERS

The engine thermometers hitherto used belong to one or other of the following types, vapour pressure, liquid pressure, gas pressure and electric. The first three have found favour in the British, American and French Services, while the German Service adopted in great measure the electric type. Improvements in thermometry have been called for by the need for registering temperatures below that at which the vapour pressure type can be regarded as reliable, and much work has been done by Messrs. Negretti and Zambra in developing

the mercury in steel type, which is now so well known as to need no further description here.

This type, however, while more accurate than the vapour pressure type, particularly at temperatures below 50°C., has the defect that it is useless below about −39°C. owing to the freezing of the mercury and the principle is therefore not suitable for universal application.

To meet the demand for a distant reading air thermometer capable of reading the lowest temperatures recorded on aircraft, Messrs. Negretti and Zambra have developed an instrument of the gas-filled type, wherein the bulb

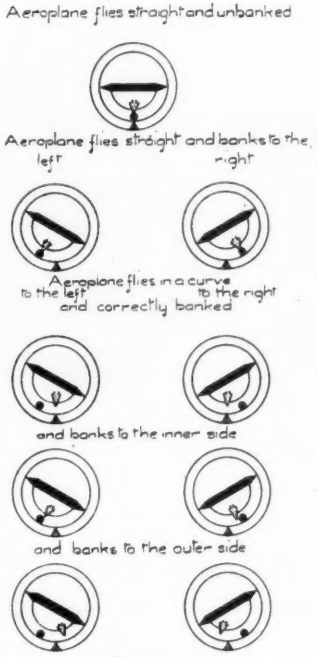

Aeroplane flies straight and unbanked
Aeroplane flies straight and banks to the
left
right
Aeroplane flies in a curve
to the left
to the right
and correctly banked
and banks to the inner side
and banks to the outer side

FIG. 23.
Indications of Gyrorector.

and capillary are filled with nitrogen at a pressure of about 1,600 lbs. per sq. in. In general design it is similar to the mercury in steel type. On air test it has been found satisfactory, the errors due to (*a*) calibration being within 0.5°C., (*b*) an altitude of 30,000 feet being within 1.5°C., and (*c*) change of capillary temperature of 65°C. being not greater than 1°C.

Strut thermometers have been improved by increasing the range so that it now extends from −60°C. to +60°C. and at the same time reducing the weight of the instrument.

PRESSURE GAUGES

Pressure gauges have remained substantially unaltered in design, development being directed mainly towards improving the construction in details to ensure a more reliable instrument.

The provision of a fluid transmitting system whereby the gauge may, in multi-engined aircraft, be placed at a distance of 20 feet or so from the engine forms one interesting modification. This system comprises a flat elastic diaphragm as in the Negretti and Zambra instrument, or a metallic bellows as in the Aera instrument (Fig. 24), which serves as a septum between the oil and the non-freezing transmitting fluid—usually paraffin.

Both these systems work satisfactorily and give reliable indications of oil pressure even when the temperature of the atmosphere, and thus of the connecting pipe, is as low as −40°C. Such distant reading pressure gauges are no more difficult to instal than radiator thermometers.

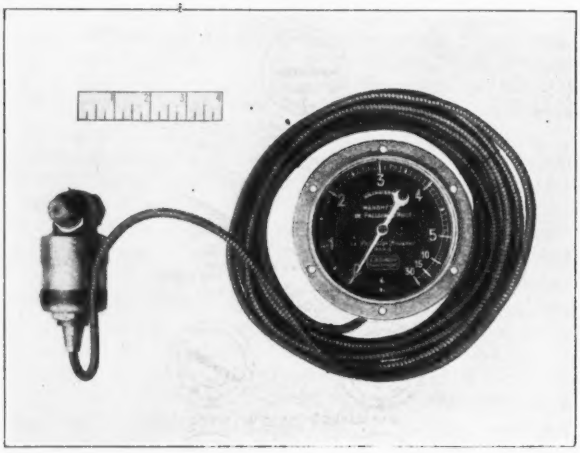


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FIG. 24.

REVOLUTION INDICATORS

The principal instruments in past and present use may be divided into the following classes:—

1. Centrifugal.
2. Chronometric.
3. Electric.
4. Magnetic.
5. Hydraulic.
6. Viscosity.

The centrifugal instrument has found most favour in this country, and indeed in America, and may be said to have fulfilled its purpose with efficiency. One difficulty, however, occurs with its use in multi-engined machines, namely, the trouble experienced in transmitting its indications accurately and in a reliable manner at a distance from the engine exceeding, say, 24 feet, a difficulty it shares with the chronometric type. In consequence the indicator itself has been improved only in detail with the object of making the instrument more robust and of lighter construction. Fig. 25 shows an indicator by Smith and Sons, which is representative of modern practice. The persistent trouble experienced with long flexible drives has led to (1) improvement in the method of driving, and (2) the development of the electric and hydraulic types of indicator. It is,

however, not yet possible to say that the revolution indicator when placed at a distance of say 25 feet from the engine is as reliable as when placed at a distance of 10 or 15 feet. The improvements in driving mechanism have been made by (*a*) the substitution of shorter lengths of shaft and intermediate gear boxes in place of the single long length, and by an ingenious method, due to Mr. Whidbourne, whereby the rotating flexible shaft is called upon to transmit lateral instead of rotary movement. The method relies upon the fact that a flexible shaft rotating in its casing requires a very small force to displace it along its length. Consequently a lateral movement at the engine end of the shaft, which can be an accurate measure of the speed at that end, can be transmitted over a length of 50 feet or more by the translatory movement of the rotating shaft to an indicator on the dashboard.

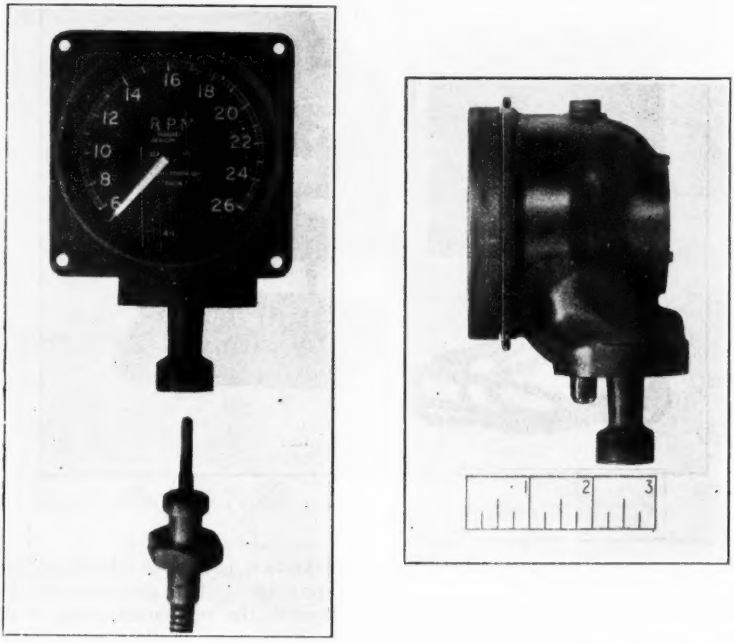

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FIG. 25.

A dual instrument, devised by the writer some years ago as a result of a conversation with Mr. Handley Page, has found some favour with the pilots of twin-engine machines, and has been suggested again more recently for three-engine aircraft. This consists of an indicator having a single dial and two pointers, one red and the other green, each driven by a flexible shaft from the port and starboard engine respectively. When the engine speeds are equal one pointer lies above the other, and at any time the difference between the speeds of the two engines can be read instantly from the gap between the two hands.

Considerable attention has been paid by makers of electrical instruments to the production of a reliable revolution indicator which shall:—

(1) Be correct within ±10 r.p.m. over a range of 600 to 2,600 r.p.m.
(2) Require very little attention.

(3) Withstand damp salt air and dusty air.
(4) Withstand vibration.
(5) Retain accuracy over wide variations of temperature.
(6) Be of reasonable weight and preferably not more than a mechanical instrument complete with flexible shaft.

Most of these points have been met except (5), but undoubtedly the instruments so far constructed require more attention to maintain in service than the mechanical types, and this may be expected.

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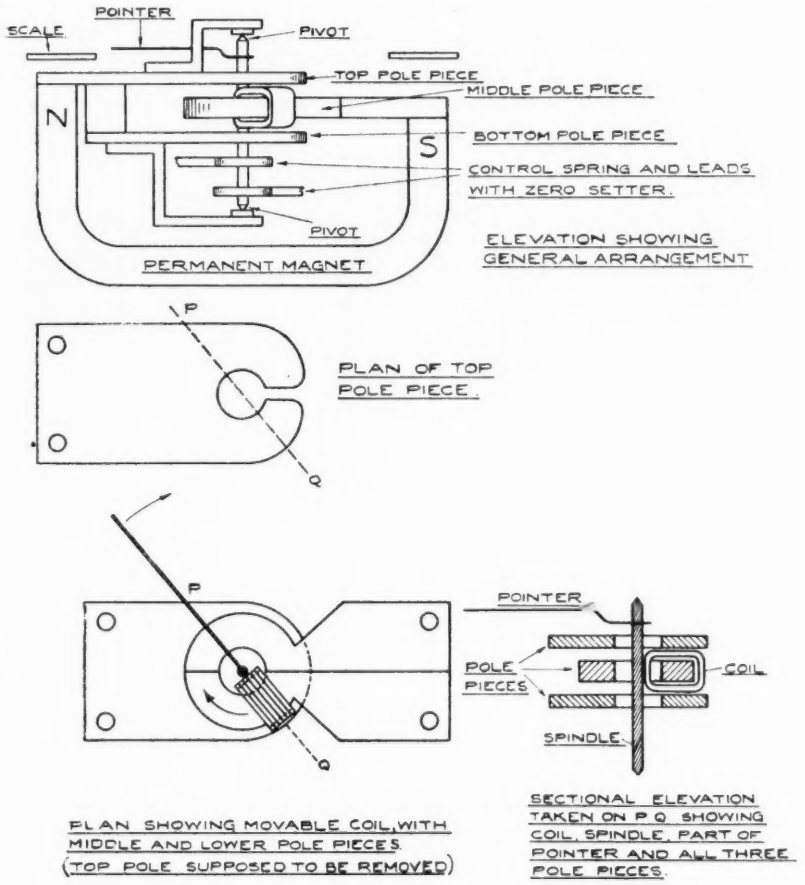
FIG. 26.

Fig. 26 shows an instrument by a well-known maker of electrical instruments based on the dynamo and voltmeter principle. The generator is driven from the engine by a short flexible shaft and is of the permanent magnet direct current type. The magnets are suitably aged to meet working conditions of temperature and vibration and the axial length is so proportioned to the gap as to maintain permanency of calibration. The generator is shielded and is waterproof. The indicator, which is a proprietary voltmeter, is shielded magnetically, but is subject to temperature variation. It is of the long scale type, a diagrammatic sketch of which is shown in Fig. 27. The movable coil carrying the pointer swings between two soft iron plates attached to one pole of the permanent magnet and is threaded on a ring-shaped soft iron cone bolted to the other pole of the magnet. The scale of the instrument is nearly uniform over an arc of about 270°.

The error of such instruments from all causes except that of temperature is of the order of 20 r.p.m.

Tests extending over long periods in temperate and tropical countries of modern instruments of this type show that they retain their calibration and are free from breakdown. They are, however, somewhat difficult to manufacture to the order of accuracy required.

An electric revolution indicator, made by the Cambridge Scientific Instrument Company, is based upon the rate of charging and discharging a condenser. Slip rings driven by a short flexible shaft serve to connect a condenser alternately with a battery and with a galvanometer during each revolution. The discharge occurs so rapidly that a steady reading is obtained. If sufficient time is allowed the condenser becomes fully charged and discharged and the quantity of electricity



DIAGRAMMATIC SKETCHES OF LONG SCALE, MOVABLE-COIL INDICATOR FOR ENGINE TACHOMETER (RECORD ELECTRICAL CO)

FIG. 27.

in each discharge of the condenser is proportional to the capacity of the condenser. This type of instrument has received considerable attention in America and a description of a modern example has been published.*

* *Journal of the Optical Society of America and Review of Scientific Instruments*, March, 1926.

The instrument is susceptible to change of battery voltage and to change in the capacity of the condenser with temperature. Attempts have been made from time to time to produce a type of electric revolution indicator depending for its principle on the frequency with which a circuit is made and broken. So far this type has not achieved the accuracy and reliability necessary to permit of its extended trial. Attention has been paid in this and other countries to the hydraulic method of indicating engine speed. The instruments made in this country some years ago fell far short of the mechanical and electrical instruments in accuracy and reliability, but more success was obtained in an example of continental origin. Tests on a sample instrument, however, showed the lag to be in excess of that found in mechanical and electrical indicators, and this lag became more noticeable with sudden variations in speed. Oil leakage trouble was also found to arise.

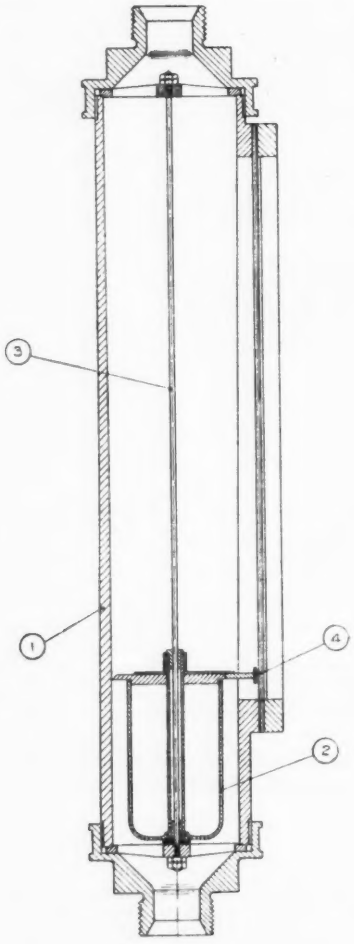


FIG. 28.

Revolution indicators based on the magnetic and viscous drag principle have shown themselves to be far too subject to temperature variation to permit of their use in service, and no instruments of these types are under development.

A point worthy of note in relation to revolution indicators for use in aircraft is that of lubrication. Frequent trouble has been experienced in high altitude flights, due to the thickening of the oil or grease, with the result that the indicator has become not merely unreliable but useless. It is necessary to ensure by actual test that any lubricant used will retain its properties at a temperature of $-40°C.$ to $-50°C.$, for experience has shown that the special oils usually recommended for low temperature work are not free from thickening at the temperatures indicated. The experience gained by a lengthy series of tests is that the instruments will themselves function at low temperatures, but the lubricant used in their assembly normally prevents them doing so.

Fuel Flow Meter Designed to Measure Mass Flow

To meet the demand for a more accurate type of fuel flow meter than the well-known vane type, a critical summary was made of all the known types, and effort was finally concentrated on the sink and tube type, which had, however, in the past given poor accuracy, owing to the neglect of the fundamental principles of fluid motion. A re-design of the instrument was made by Dr. Griffith and Mr. Kerr.

The most important features of the instrument described here are:—

(1) The instrument measures mass flow.
(2) The readings are independent of density changes over a wide range.
(3) The readings are practically unaffected by variations in viscosity.

A sectional elevation and plan of the instrument is shown in Fig. 28. The brass tube 1, tapered outwards from bottom to top, contains a sink 2 which is kept in a central position relative to the tube by a guide rod 3. The metering orifice is the annular space between the tube and a concentric sharp-edged disc fixed to the sink. Since the tube is tapered, the area of the orifice varies with the height of the sink in the tube. A narrow slot covered with mica and a tongue 4 projecting from the sink enable the height of the sink in the tube to be observed.

Theory of Instrument

Let p = pressure difference across orifice.
v = velocity of fuel.
ρ_f = density of fuel.
ρ_s = density of sink.
Wa = apparent weight of sink in the fuel.
A = area of sink.
V = volume of sink.
a = area of orifice.
h = loss of head across orifice.
K = coefficient of discharge.

For turbulent flow across the sharp-edged orifice we have:—

$$p = \tfrac{1}{2}\rho_f v^2$$

Also

$$p = Wa/A = gV(\rho_s - \rho_f)/A$$

Hence

$$v = (2gV(\rho_s - \rho_f)/A\rho_f)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (11)$$

The mass flow $= K.a.v.\rho_f$

$$= K.a\,(2gV(\rho_s - \rho_f)\rho_f/A)^{\frac{1}{2}}$$

It will be seen that the expression for the mass flow contains two factors involving ρ_f, namely, $\rho_f^{\frac{1}{2}}$ and $(\rho_s-\rho_f)^{\frac{1}{2}}$. As the fuel density increases the first of these factors increases and the second diminishes. The relative magnitude of the second change depends on the value of ρ_s. Hence it appears that by choosing a suitable value of ρ_s, it is possible to obtain a mean compensation for variation of fuel density due to change of fuel or change of temperature.

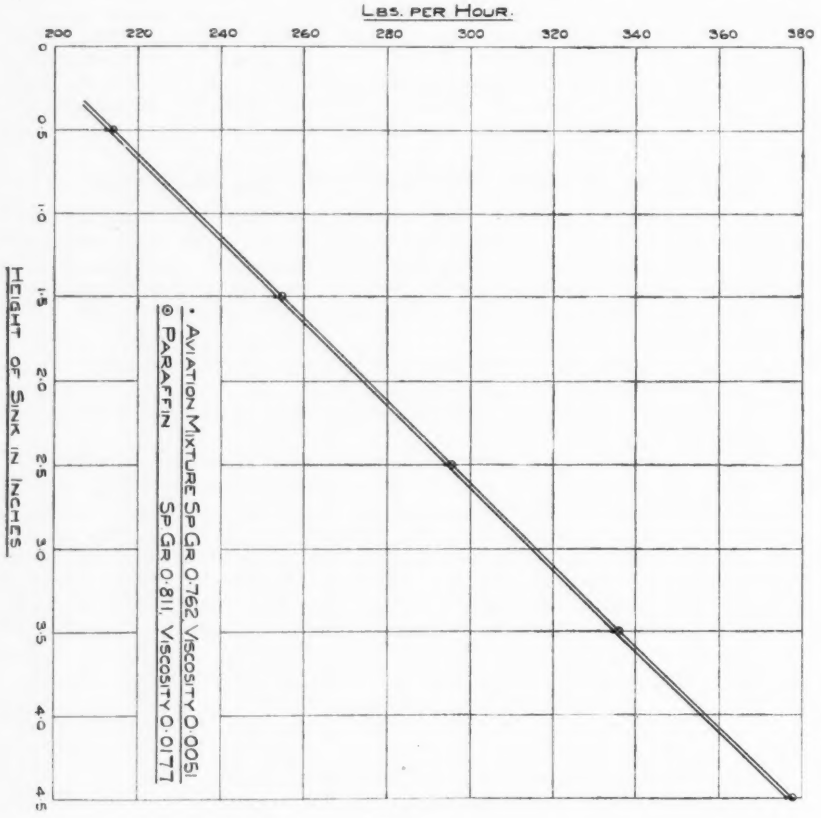


FIG. 29.

Differentiating the expression $\rho_f^{\frac{1}{2}}(\rho_s-\rho_f)^{\frac{1}{2}}$ with respect to ρ_f and equating to zero, it is found that the compensation is exact when $\rho_s=2\rho_f$. The density of the sink should therefore be made equal to twice the mean density of the fuel.

The maximum error of reading, due to the residual density effect, is only 0.25 per cent. when the fuel density varies over the range of ± 10 per cent. from the mean.

The velocity through the orifice is given by $v=(2gh)^{\frac{1}{2}}$.

Also from equation (11), putting $\rho_s=2\rho_f$

$$v=(2gV/A)^{\frac{1}{2}}$$

Therefore $h=V/A$.

The value of h is determined by ensuring that the flow is turbulent without making the back pressure excessive. In the design h is 3 cm., making v equal to 77 cm. per second.

Viscosity Test

Fig. 29 shows the curves obtained with aviation mixture and paraffin. The viscosity of the paraffin is 3.5 times that of the aviation mixture, yet the agreement between the two curves is extremely close. Using aviation mixture this viscosity test is equivalent to a temperature range of $+25°C.$ to $-30°C.$

Fuel Contents Gauges

The attempt to produce a completely satisfactory contents gauge for aeroplanes is as old as the industry, and with the modern wing tank and the demand for a distant reading instrument, the problem is still further complicated. Aircraft fuel contents gauges are numerous and of never-ending variety, but no nation seems to have become possessed of a distant reading gauge which finds general favour. Despite this somewhat pessimistic summary, however, there are gauges in existence which will give a reasonable measure of accuracy, are convenient to use and fairly easy to instal. It is proposed, therefore, to describe two instruments which have met with a fair measure of success and are being installed in aircraft at the present time.

Before proceeding with the description of the modern gauges it may be advantageous to define the conditions to be satisfied by an aircraft petrol contents gauge.

They are:—

(1) Definiteness and accuracy of reading notwithstanding the variation of pressure above the fuel in the tank.
(2) Freedom from error or derangement due to vibration, swirl of liquid, variations in apparent gravity, wide variations in the attitude of the aircraft and changes in temperature.
(3) Limited bulk and weight.
(4) Accuracy when indicating at a distance.
(5) A certain universality of application to tanks of varying shape.
(6) Ease of installation.
(7) The safety of the aircraft must not be endangered in the event of breakage of the gauge.
(8) Simplicity of construction.

Space does not permit of pointing out where many types fail to satisfy these conditions, although if many of the suggested instruments are examined their shortcomings are apparent.

The " Televel " gauge, which is of the located float type, comprises a hollow tube fitted with a rack on one side, as shown in Fig. 30, and carrying a frame D to which is pivotally connected a float E. A stiff wire C connects the frame D with an indicator on the dashboard, so that movement of the indicator by hand causes the slide to move along the tube. When the frame and attached float is moved down through the vacant space of the tank no resistance to motion takes place, but when the float strikes the level of the fuel it is raised and causes the engagement of a pawl F with the rack B, so that no further movement can be made to take place. The position of the indicator gives a measure of the depth of petrol.

Another example of this type is the " Spirobloc," which has been fitted extensively to French aircraft and has been tested with satisfaction in this country. In this a perforated cage G, Fig. 31, carries a cam surface F against

which a stop E on the float A may be caused to engage by rotating the float. The latter action is performed by arranging the float to slide freely on a squared rotatable spindle B carrying at its upper end a drum C connected by a wire to a drum in the indicator case on the dashboard. The drum is rotated by pulling the knob D; a spring on the squared spindle brings the latter and, in consequence, the stop E to the zero position.

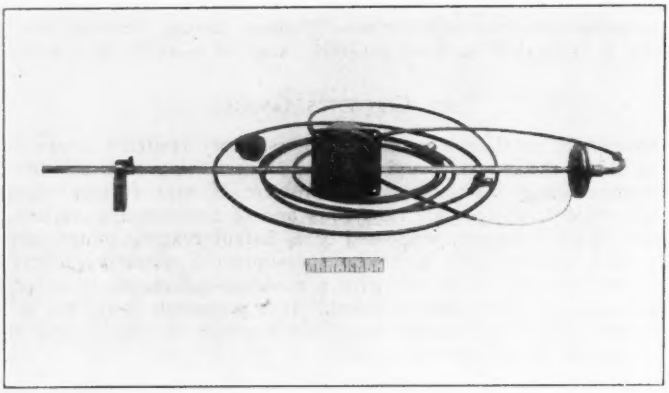


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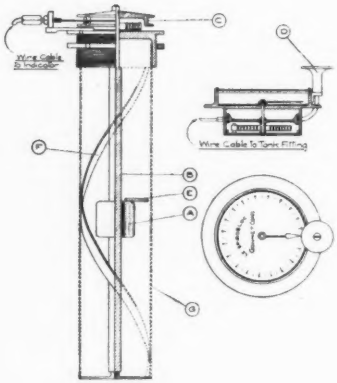
FIG. 30.



SPIROBLOC PETROL LEVEL GAUGE

FIG. 31.

This instrument is somewhat bulky and expensive to produce in varying designs.

COMPASSES

The development of the magnetic compass was described by Mr. Wimperis in the paper already referred to, and detail improvements have been made since that date. Two designs of distant reading compass, both of foreign origin,

have been the subject of test in this country, and one of these, the Earth Inductor compass, has been used with success in trans-oceanic flights, notably by Colonel Lindbergh.

The Earth Inductor compass consists of three principal parts—a generator, a controller and an indicator. The generator is the unit for determining direction and corresponds to the needle in the magnetic compass. It is similar in principle to the ordinary electric generator in that it embodies an armature, commutator and brushes, but in place of the artificial magnetic field, the earth's magnetic field is used. It will be clear that if the armature is rotated in the earth's magnetic field and the brushes are moved a complete revolution around the armature, two positions of maximum deflection of the needle of a galvanometer in circuit with the brushes and two of zero deflection will be obtained. In the earth inductor compass it is on the direction corresponding to one of the zero positions that a determination of course is made, and the armature is so arranged that a zero reading is obtained when the brushes are at right angles to the magnetic north and south.

The brushes are connected to the controller by a flexible shaft, and if connection between the brushes and the controller is made when the indicator pointer is at zero and with the controller set to the heading of the aircraft, any subsequent angle between the fore and aft line of the aircraft and the magnetic meridian can always be read off on the controller.

Fig. 32 shows the elements of the device. The armature housed within the case 1 is driven through a shaft and universal joint by the windmill 2. The

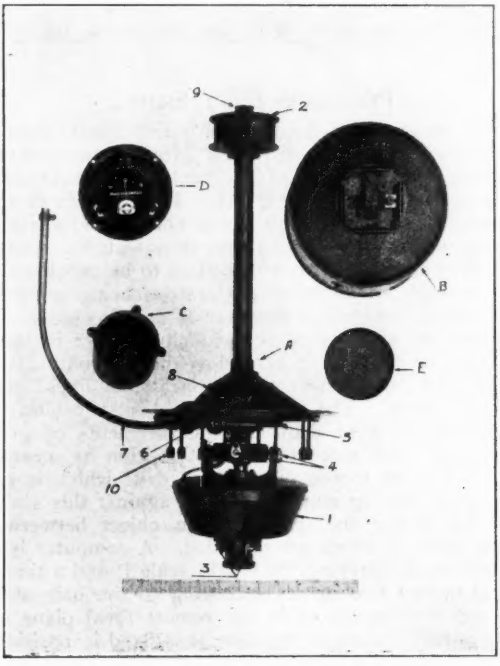


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FIG. 32.

armature case carries the brushes 3 and is pendulously mounted on the gimbals 4, which in turn are so supported that the armature case and brushes can be rotated in either direction by means of a worm-wheel 5, worm 6 and flexible shaft 7. The end of the shaft is connected to the controller C. The brushes are connected through a plug socket 8 and leads with the indicator D. Compensating magnets are housed in the cover B. The speed of the windmill can be adjusted to give the correct speed of the armature on different types of machines. The pendulous armature is limited in total movement by stops 10, and its oscillations are damped by friction pads in the gimbal ring.

The disc of the controller and the brushes are moved by a handle, but a nut is provided whereby the handle may be temporarily disconnected from the dial to allow of brush setting to correct for deviation. In use, of course, the brushes must be connected to the dial.

The armature rotating at a speed of 2,200 r.p.m. is stabilised gyroscopically. Any displacement of the axis from the vertical is rectified by a spiral erection, which causes the indicator pointer to oscillate about the zero position. The total time taken by the pointer to return to zero after a maximum displacement is approximately eight seconds.

The complete instrument weighs about 14½ lbs. and is fairly reliable mechanically, some trouble having been experienced with a dirty commutator and with breakage of the indicator spring. These are defects which should be easily removable. Indefiniteness of location, due to backlash in the transmission system, of the order of 1° has been experienced.

A drawback with such an instrument is that owing to the occurrence of two zero positions 180° apart, the pilot must ascertain which is correct for the desired course. This is done by making a slight turn and noting the direction in which the pointer moves.

Periscopic Drift Sight

This instrument, designed at the Royal Aircraft Establishment, is primarily for use on civil aircraft to enable drift and ground speed observations to be made without leaning over the side of the cockpit. The instrument is shown in Fig. 33 and the optical system in Fig. 34. The eyepiece is so arranged that the observations may be made without much change of position although the head is in proximity to the rubber eye shield shown at A. At the outer end of the periscope a small roof prism is so attached as to be capable of rotation about a transverse axis through an angle of 22½°, stops being provided to limit the movement. The prism is rotated by the lever H and linkage J. In one extreme position of the prism the object seen is vertically below; in the other extreme position a view under the tail and at 45° below the horizontal, is obtained. The instrument contains two independent sets of graticule lines, one for use with each position of the prism. The graticule fixed just behind the eyepiece is used for taking the direction of drift and measurements of ground speed. It is rotatable through 50° each side of the zero position by means of the ring C and the longer lines are set to the direction of drift which is read against the scale D. The compass bearing may also be set against this scale. The ground speed is obtained by timing the transit of an object between the transverse graticule lines, two pairs of which are provided. A computer is attached to the instrument, a milled ring L carrying the height scale P and a time scale N, which may be set against one of two marks according to the pair of transverse lines used. The other graticule is placed in the remote focal plane of the periscope and consists of a graduated scale of degrees; it is fixed in position with the scale horizontal. If now, when the prism is in the position for viewing objects vertically below, an object is seen to cross the centre point of the field of view, it can be followed by rotating the prism until the latter comes against the stop at the

other extreme of its motion. The point at which the object is then seen to cross the fixed graticule scale gives the direction of drift with reference to the fore and aft line of the aeroplane. This method is used for finding drift from a tail bearing.

A cover G is provided to protect the prism from oil and dirt when not in use.

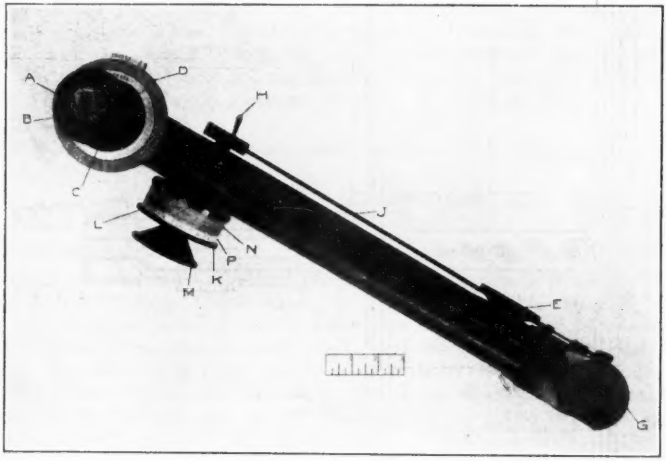

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FIG. 33.

TAIL DRIFT SIGHT

This instrument, designed at the Air Ministry Laboratory and modified by the Royal Aircraft Establishment, is a compact lens and mirror system for obtaining drift from tail observations. It consists of three parts:—

1. A quadrant A fixed to the aircraft in which an Aldis tube and mirror rotates.
2. An Aldis tube B and mirror device.
3. An operating lever and pointer.

Fig. 3 shows the instrument. An Aldis tube B is arranged inside a sleeve C which carries at its lower end a box D containing one fixed mirror E and one moving mirror F, the tilt of which can be adjusted by rotating the Aldis tube through linkage. Attached to the sleeve is an operating handle and a pointer

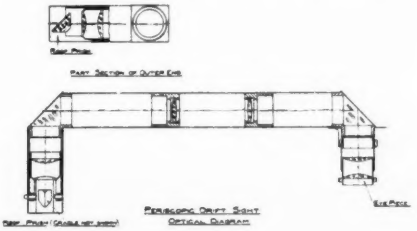

FIG. 34.

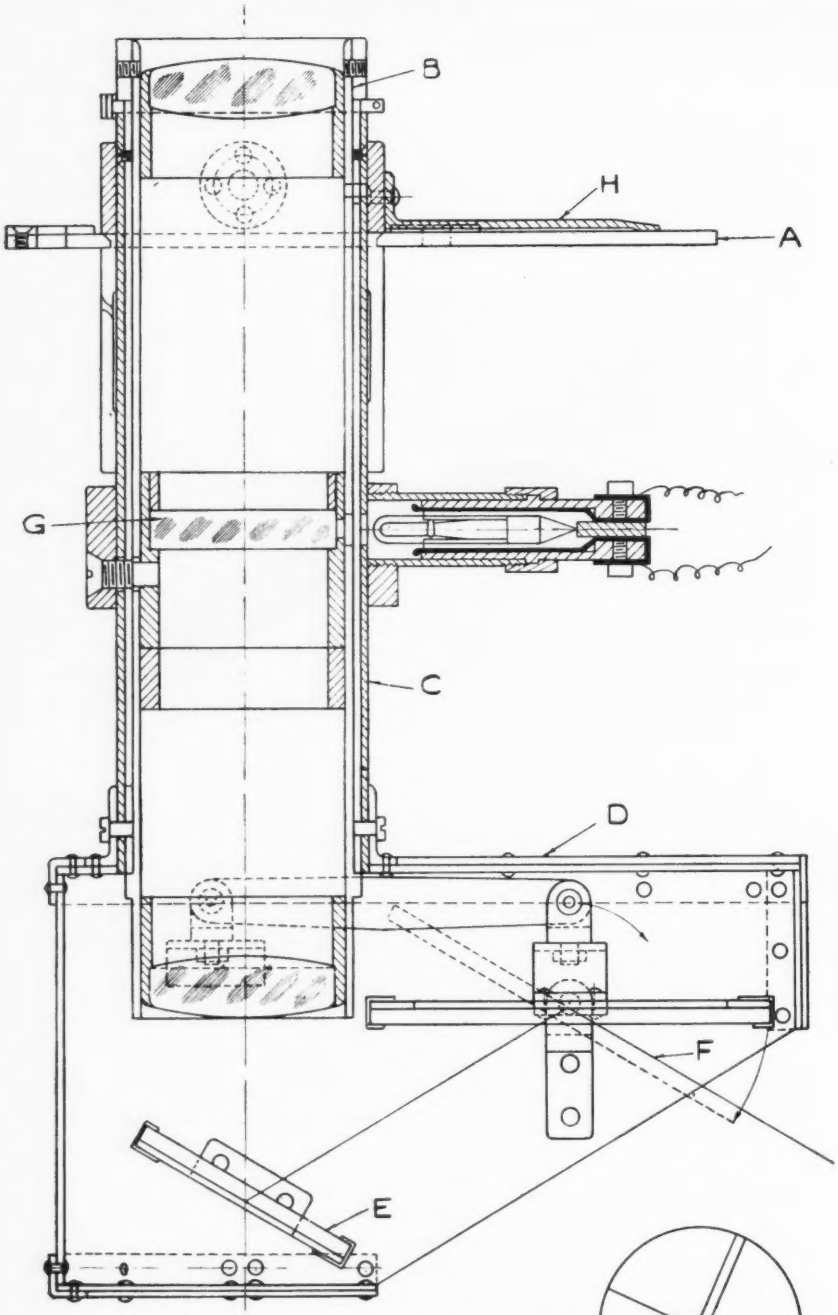

FIG. 35.

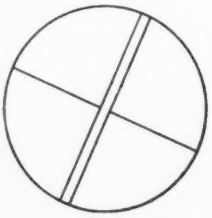

FIG. 35A.

H working over a graduated quadrant secured to the bottom of the aeroplane in such a manner as to form the support for the instrument.

A glass graticule (G) is mounted on the sleeve by means of screws passing through slots in the Aldis tube and thus moves with the drift operating handle and not with the Aldis tube. By this means the drift lines on the graticule always follow the mirror system on rotation.

In use the moving mirror is adjusted to one end so as to reflect an object immediately below the machine to the eye by way of the fixed mirror and Aldis tube. As the ground object recedes the mirror is tilted by the rotation of the Aldis tube, and the object is kept in view by simultaneous adjustment by the handle. The position of the pointer on the graduated quadrant gives the angle of drift. The instrument is accurate, easy to use, and is adequately protected against dirt.

Wind determination can be obtained by the double drift method with this instrument.

For use at night the method of total reflection by light thrown in at the polished rim of the graticule has been used.

Fig. 35a shows the appearance of the graticule in the field of view.

In conclusion we cannot do better than repeat the words of Sir J. J. Thompson, Master of Trinity College, Cambridge, " You cannot run the industries of to-day upon the science of yesterday," and to hope that interesting and ingenious though the modern aircraft instruments are, their successors in simplicity and accuracy are already in existence in embryo. It may with some truth be urged that the altimeter is as old as the aneroid barometer, the air speed indicator as the diaphragm gauge, the revolution indicator as the Watts governor, and that the application of science has merely improved the design for new conditions rather than suggested a fundamentally different design.

Again with truth it may be urged that a limit must soon be set to the amount of detail improvement which should be laboriously imposed upon these old designs to enable them to meet modern conditions of usage, and it may not be too optimistic to say that future lecturers on this subject will be able to exhibit proved instruments which bear little or no resemblance in design to those already described.

The inconoclasts are attacking with theory and endeavouring to establish a new practice as evidenced by the Rate of Descent Meter, the Flowmeter and the Earth Inductor Compass.

Devices of a more purely research nature for air speed and engine speed measurement are being experimented with, and success, which must, sooner or later, be achieved, will, it is hoped be accompanied by instruments of a greater simplicity.

Discussion

The Chairman: I have listened to Major Stewart's paper with very great interest indeed, in fact, I do not know how he managed to condense so much information into the space of one hour as the paper itself would take nearly two hours to read.

I will ask Mr. Wimperis to open the discussion.

Mr. Wimperis: I think it was an excellent idea of Major Stewart's to bring the knowledge of the Society in respect of aircraft instruments quite up to date.

I am glad to see that Major Stewart has mentioned the names of his staff who have specially helped him in these investigations. He is very fortunate in having an exceedingly able staff, and I recognise with pleasure the credit he is able to give to several specific individuals. It must, however, be remembered

that there are instrumental investigations which by reason of their confidential nature could not be described, but had the lecturer been free to do so he would have been able to mention the names of certain other officers who are at present anonymous.

I read the paper before coming here this evening, and found parts of it rather difficult to understand. For instance, I had to confess that I previously had no idea of what a " thermostatic helix " might be. I knew, of course, that the human body was rightly described as a thermostat because it maintained its temperature at 98.4 deg. Fahr., or thereabouts, but I do not think there is anything in an aeroplane which does anything of that kind, and I suspect that constancy of dimension rather than constancy of temperature is the aim of the " thermostatic helix." No doubt the lecturer will tell us.

I should be glad if the lecturer could state the reason of the substitution of iron for brass in the construction of the bosses which so materially assist in reducing temperature effects.

Those are the chief points I wanted to bring out in reference to my difficulties in following certain parts of the paper. I did not have any difficulty in following the gyrorector, because I had had the opportunity of reading the paper previously. In connection with this, I was rather sorry when reading the paper to find no reference to the Lanchester pendulum, which seemed to be the direct ancestor of this device. I was very glad, therefore, to notice that the lecturer did mention it in expounding his MS.

A big tribute is paid to the success of a particular altimeter. The C. tests described on that page are certainly wonderful. When we think that they range from 0 to 30,000 feet, and that the changes at zero are but 15, 50, 30 and 80 feet, it is a most marvellous advance in altimeter construction, and reflects the greatest credit on British instrument makers.

Some of you may be aware that in accordance with the theory of relativity it is not possible to distinguish between gravitational acceleration and ordinary acceleration. If that is the case, how is it possible that any device, gyrostatic or otherwise, can claim to indicate the vertical in an aeroplane? Well, it does not do so, but it makes a good shot at it, and I think the matter is most simply described by saying that whereas an ordinary pendulum will take up the direction of the apparent vertical and will give no indication of the real vertical; nevertheless, if the aircraft in question is fitted with a gyroscopic turn indicator and an air speed indicator, you can multiply the air speed by the angular velocity, and so get the lateral acceleration and hence compute the allowance for the angle by which the pendulum has been thrown out of the vertical. That is, I think, the simple explanation of the reason why it is possible to devise an instrument that can give you the vertical with tolerable accuracy. Its weak point is that the lateral acceleration you are getting depends on the axis about which you are turning, which may not be vertical.

We are all very relieved to hear that a satisfactory flow meter is in sight, and I hope no practical difficulty will prevent it becoming a standard instrument. The difference of fuel consumptions on two identical machines on identical duty is so large that if we could get maximum accuracy on all machines there would be a resultant saving which would pay many times over for the whole of Major Stewart's staff at Farnborough.

With reference to the earth inductor compass, I should like to point out what is the particular advantage of this instrument. You cannot get away from iron and steel in the neighbourhood of the pilot's cockpit. If to decrease deviation error the compass is put near the tail of the aircraft, or some form of " distance reading " arranged, it is of necessity being put where, during flight, no one can look at it, or adjust it, and that is a dangerous position for any instrument on which you rely for safety. I think, therefore, that if the earth inductor

compass comes into general use (though I do not say that it should), it will always be necessary to fit also one of the older types of magnetic compass either in the cockpit of the pilot or of the navigator.

Mr. BRAMSON: One of the first instruments to which the lecturer referred was the double diaphragm air speed indicator. I have had some experience in trying to make such an instrument, and have failed, due to the difficulties to which he has drawn attention, of getting the right material.

One point the lecturer explained was that there is a thin and a relatively thicker diaphragm, which together form the diaphragm box. At a certain pressure the thin (weak) diaphragm becomes inoperative, and the remaining readings are due to the deflection of the thicker one. Under these circumstances the weaker diaphragm is supported by a shroud. The change-over is, however, rather difficult to define. The corrugations come into contact one by one with the shroud, but at what pressure is the weak diaphragm completely supported by the shroud? Attempts have been made to construct an instrument in which the change-over from 2 to 1 diaphragm is definite and adjustable to occur at a convenient pressure. One would like to know whether such a definite change-over is considered advantageous.

In connection with rate of climb or descent indicators, it occurs to me that there is one principle on which one might possibly base the design of such an indicator, which would conceivably be less complicated than the most modern one to which the lecturer has referred, that is, by a combination of an indicator of air speed and an indication of the angle which the path of the machine makes with the horizontal. The angle can be measured as the difference between the position of a line at right angles to a pendulum freely suspended in a vertical longitudinal plane, and that of a balanced vane stably suspended in the air stream and similarly pivoted so that its angular position is determined by the air streamlines. If the air speed is multiplied by the sine of that angle the rate of vertical climb or descent is obtained, and it seems to me it might be possible to get a purely mechanical instrument which would give the measurement in that way.

I should also very much like to know why no advance has been made with the hydraulic distance reading revolution indicator. It seems to me that such an instrument might have quite definite advantages over the electrical type.

Finally, I would very much like to agree with what Mr. Wimperis said about the necessity of using the ordinary compass in addition to the earth inductor compass. I think that such instruments as are indispensable for the safety of aircraft should be duplicated in one way or another.

Mr. CAPON: One naturally thinks of development and research in instruments as a rather prescribed science. Some may have thought that all that is necessary is to be able to hold a watchmaker's eyeglass in the eye and to have a certain mechanical ability. Major Stewart has effectually dispelled that idea to-night. He has shown that a very wide range of scientific knowledge is essential for progressive and successful work in instrument design. During the lecture I was listing the branches of physics concerned in the work we have had described to us to-night, and it soon became evident that there were not many sub-divisions which the paper did not touch upon, directly or indirectly. One which I had thought had not been referred to—the Principle of Relativity—the first speaker has shown was tacitly included.

Major Stewart has shown us the extraordinary accuracy in instruments which is obtainable now, and the way in which an instrument can be provided to meet practically every emergency. There is one aspect, however, which is not quite so satisfactory and that is the difficulty that sometimes occurs in getting instruments adopted after they have been adequately developed. In 1919 I tested a turn indicator on which I made a favourable report. In 1920 and 1921 I had three

turn indicators of different types fitted to aircraft that I was flying, and which were, in my opinion, practically satisfactory. There is still no standard turn indicator in use, and the reason for this appears to be that one cannot get any definite opinion from pilots as to whether the turn indicator is useful or not. All the types I have used have been satisfactory to the extent that it was possible by their use to keep a sufficiently straight course in cloud, and to recover when the aircraft had been momentarily put out of control; but apparently quite a number of pilots think that no satisfactory turn indicator has yet been produced. The only suggestion I have to make on the matter is that pilots should not report on an instrument until they have had 15 or 20 hours' flying with it.

I think Major Stewart is to be congratulated on having compressed into the time available an account of the present position of instruments research and development, which not only provides the type of general information required by the non-specialist, but which also gives a very full account of the guiding principles in present-day instrument design.

Squadron-Leader ENGLAND: We are very greatly indebted to Major Stewart for his paper this evening, because he has been permitted to disclose that two most important instruments have more or less passed the experimental stage. I refer to the flow meter and the rate of climb and descent meter. Both these instruments have been sadly neglected and their need is very great.

The last speaker made a very apt remark when he stated that pilots, as a body, do not take kindly to new instruments. I imagine that the reason for this is that, taking the pilot's cockpit in a standard production aircraft, there are from 12 to 18 instruments, which from time to time the pilot has to observe, and therefore any new instruments which are devised only add to the excessive number and are looked upon with disfavour. Not only does the pilot feel that there are too many instruments, but the designer and constructor has of necessity to make an excessively large cockpit for the purpose of housing instruments in a somewhat antiquated manner. I feel that whilst progress has been made in the design and perfecting of the actual instruments, little has been done with a view to grouping together the instruments and reducing their number to the minimum consistent with efficiency.

We have a good illustration of this in the different practice in the British and American motor car trades. Omitting possibly one or two exceptions, British manufacturers have instruments which are spread all over the dashboard, while the American manufacturer has the same number of instruments, if not more, contained in the one panel, with a practical system of instrument lighting, the whole panel occupying one-third of the space on the dashboard to that of the British motor car. I therefore think that this obvious lesson should be applied to aircraft, and the prejudice against confining instruments into a small space would be lived down.

The reason given why the turn indicator has not become more popular has been attributed to the pilots. No doubt this is correct, because a correctly designed turn indicator reveals the inaccuracies in piloting, and therefore, to a pilot of experience, is not altogether welcomed.

I was rather disappointed to hear the Lecturer's remark in regard to the electrical revolution counter. He stated that manufacturers had not taken kindly to it. I presume he refers to instrument manufacturers. If their hostility towards this instrument is due to the difficulty of manufacture, it is regrettable that such a useful instrument should have been designed in a complicated manner.

The various altimeters which have been described and illustrated to-night, do not appear to have any insulation against vibration. The type of altimeter now used may have minor errors, but nevertheless is extraordinarily reliable if and when it can be mounted on an instrument board, eliminating vibration.

Another point whilst perfecting air speed indicators, and in these days of improved control, is that a false reading at slow speeds is bound to be obtained unless a swivelling pitot head is used. Whilst swivelling pitot heads are used at experimental establishments, I suggest that these are still far from being altogether satisfactory, and should like to hear the Lecturer's comments on this point.

Mr. C. B. Collins: Regarding the earth inductor compass, the question is often asked by civil pilots—particularly in connection with long distance flights —" Ought I to have an earth inductor or a magnetic compass?" This is difficult to answer, because we in civil life have not had any practical experience of the earth inductor compass.

Out of four actual long distance flights on which, according to my recollection, this compass was used, it broke down, I think, on three occasions, the successful occasion being, of course, Col. Lindbergh's Atlantic flight.

Compared with the *very* simple component parts of the standard British magnetic compass, it looks a very elaborate piece of mechanism which might easily get out of order. So far as I can understand it, its particular advantage lies in the fact that the generator or " business " part of the compass can be housed in that part of an aircraft where coefficient Lambda is highest, and where coefficients A—E are lowest, whereas the " indicator " or actual record of the course can be placed on the instrument board in a convenient position for the pilot. It does not, as some people imagine, dispense with corrections for variation and deviation.

If this conception is correct, perhaps Major Stewart would tell us whether the instrument has yet reached that stage of perfection which justifies its *substitution* for the magnetic compass. If not, then I see no advantage in carrying it at all, since the magnetic compass when properly installed has reached a very high standard of reliability and accuracy and deviations from the course set of the order of one degree can easily be detected.

With reference to oil pressure gauges, I quite recently came across a lecture given in U.S.A. by Mr. C. H. Biddlecombe (formerly of the Civil Aviation Department in this country) on the Wright Whirlwind engine, in which he said: " In this connection I would express the opinion that oil pressure gauges are by no means entirely reliable guides as to what is happening inside the engine. In a number of engine designs it is possible to have a normal pressure reading with a very restricted oil-flow, due to either a screen or a pipe-line that has been partly clogged with dirt or carbon. The result is frequently a frozen bearing with a uselessly short warning from the thermometer. An oil-flow meter, indicating circulation instead of pressure, would be of considerable value to the aeronautical engine, as such an instrument would indicate a falling-off in the oil-flow long before the pressure and temperature gauges would do so."

I should like to ask if some form of oil-flow meter has really been considered in this country as an alternative to the oil pressure gauge.

In conclusion, I would like to offer my congratulations to Major Stewart for his very valuable lecture, which makes it clear that our aircraft instruments have greatly improved in reliability and accuracy during the last few years; a fact which justifies a query as to whether the instruments themselves are understood and used as much as they might be, by the people for whom they have been devised. I feel that pilots should make continual use of them at all times, to such an extent that the interpretation of their various indications becomes entirely a sub-conscious effort. It is only by such constant practice that we are going to increase the reliability factor in commercial flying, and at the same time bring the day nearer when regular night flying will be in operation, since flying by instruments rather than by human judgment is essential to this achievement.

Captain ENTWISTLE: I was particularly interested in Major Stewart's account of the work which has been done at Farnborough on the altimeter, which has resulted in the production of an instrument in which an attempt is made to correct more closely for the actual variations of temperature, etc., that may occur. There is one correction, however, for which an altimeter, however perfect it may be, makes no provision, and that is the correction due to the horizontal variation of atmospheric pressure, which is really very important. Even on the short regular routes such as the London-Paris route, the correction due to this cause may easily amount to over 200 feet, while in the case of a long distance flight it may amount to as much as 1,000 feet.

It is difficult to see how one could devise an instrument to correct for both vertical and horizontal variations of pressure. At present the difficulty is got over as far as the regular air routes are concerned, by supplying pilots with an altimeter correction chart before they leave Croydon, on days when there is likely to be fog or low cloud along the route.

It would be interesting to know whether this problem has received any consideration at Farnborough, and whether there is any likelihood of an attempt being made to meet it.

Mr. COOKE: I congratulate Major Stewart very much on his lecture, and *particularly* in regard to the mathematics he has given us, because I myself have failed to understand them. There is, however, some consolation in that we may safely rely on Major Stewart in that respect.

Major Stewart has dealt very thoroughly with the theoretical considerations underlying the several instruments, and it is evident that much patient work has been done in that direction, but to my mind, the question is whether *construction* should not be given some entirely different forms if further real improvement is to be produced.

As an example, we have the results given regarding the big improvements made in altimeters. By improving the design of the aneroid box, or so-called capsule, on theoretical grounds, the lag was improved—reduced, that is—in the proportion of 2:1. After that, by selecting material, a further improvement of $3\frac{1}{2}$:1 was effected, and even again after that it was possible to achieve a further improvement of $7\frac{1}{2}$:1 by change of what one may call "design," as distinct from theoretical calculation. This new altimeter seems a very fine development, but evidently practical considerations have done much more than theoretical.

Major Stewart remarks also in reference to these same capsules as used in air speed indicators, that the mere substitution of steel bosses for the usual brass ones has made a great difference in certain cases, but unfortunately there is no definite explanation of this. It can only be due to expansion with temperature, and as the coefficient of brass is much more nearly that of nickel silver than is that of steel, the effect is contrary to theoretical explanation, and must be due to internal stress consequent on the stamping, which is obviously beyond calculation. He also remarks that owing to "our national character" we demand a 16-inch scale when other nations are satisfied with a 5-inch. I think he means that in this country the Ministry are not satisfied with something which "will do," but want something that is really perfect, even if it is something that no one can produce. They are therefore aiming high and ever higher, and I hope they may attain their end—if ever there is to be one.

With regard to the air speed indicator, I am wondering how necessary air speed really is and how true it need really be since it does not take drift into account. The only time we want to know mere air speed is when approaching a stall. It does not help from the navigational point of view unless you also know the movement of the wind.

Major Stewart has made no mention of any improvements with regard to the weight of instruments. That is an important point which he and his colleagues

are always impressing on manufacturers. He only mentioned the total weight of one instrument—the gyrorector—as being 35 lbs. That is certainly remarkable; probably it is more than the weight of all the others put together. It is certainly fifteen times the weight of the British turn indicator described.

With regard to weight generally, I suppose there is no finality and the general idea is to keep everything light. Yet, after the instrument maker has managed to scrape off another half ounce, he finds other folk cheerily loading on board a Verey pistol weighing 6 or 7lbs. Major Stewart might direct attention to that.

Another question is that of accuracy, to which Major Stewart has paid considerable attention. One speaker remarked that he had tested many turn indicators and found them all satisfactory. I presume he meant that when he turned they all showed that he was turning. I suppose that any turn indicator would be satisfactory in the air under such a test, but the real problem is to find out what such instruments actually indicate. As we have already heard from another speaker, the pilot is often humbled by finding that his instruments are better than he is. The turn indicator to be of any real use must be more sensitive to turning than he is. It must be able to indicate a turn which is so slight that he believes he is still flying straight. It must also be consistently accurate for turns to right and left. That was the problem, and the turn indicator, to be useful, must pass a very severe laboratory test in these respects before it can even be offered to the pilot as a serious instrument. Those earlier types failed in the laboratory. Another important consideration is the human factor. The instruments must be such that the pilot can make use of them within his own limitations. A turn indicator is not for fair weather, but for bad, and has only to be used when the pilot is flying under stress and natural anxiety. That the Air Ministry may have been rather unfavourable to any instrument may have a simple explanation also in this fact alone. In the gyrorector we have a splendid example of what, I submit, an aeroplane instrument dial should not be. You have four pointers to watch—just little fingers that move about, and you have to determine what is happening by the *relative* positions of all these. I suggest it would all be rather difficult to follow, and that all the instrument does clearly is to show when you are flying level. Even so, the cross-arm cants to port to show that the machine is canting to starboard, and *vice versa*. That seems a most undesirable complication to impose on a harassed pilot. On the other hand, the turn indicator that is receiving approval here shows *nothing* when the machine is flying straight. A red light appears to indicate a turn to port, and a green light to show a turn to starboard. These lights increase in size as the rate of turn increases. The meaning is obvious. I would indeed have indication by colours on some of the other instruments. Oil pressure gauges could be simplified to the extent that they are in some motor cars, so that they signal when something is wrong and leave one without worry when all is well. The pointer of an instrument has to be observed and read. The eye has to be turned to, and focussed on it. The mind has to appreciate the meaning of its position; whereas, the appearance of a coloured light attracts attention to itself and declares its message at once.

In dealing with revolution indicators, Major Stewart referred to a method, devised by Mr. Whidbourne, of a rotating flexible shaft. It seems ingenious, but I do not quite understand it. The idea is apparently to cut out the whip in the shaft, and allow the movement to be directly coupled to the engine to be kept warm by it. It must, however, be a very small longitudinal travel, and in view of expansion with temperature, and the " stop " due to general backlash, it seems to me that the difficulty must be more than the advantage gained.

With regard to the flow meter, the descriptions were very interesting. I was rather surprised to hear that the readings are constant irrespective of the viscosity of the liquid, since turbulence, which must necessarily vary with the volume passing,

seems such a very unstable basis. I notice in the example given that the calibration, converted from pounds to gallons, ranges from 25 to 50 gallons per hour, and that 25 gallons is indicated by only half an inch on the scale. Can such an instrument be constructed so as to indicate a smaller flow for a single-engine machine?

Mr. MUNRO: The very broad survey of Mr. Cooke has made it almost impossible for me to add anything to the discussion.

We are all very grateful to Major Stewart for his paper, but there is one point about which I think he might have spoken, namely, that the information contained in his paper should be brought to the notice of those who have to handle the instruments in the Service. The instruments are manufactured with the greatest care, and it would be satisfactory to know that they were as carefully handled by those in the Service. For that reason, therefore, I suggest that the information contained in the paper should be brought to their notice.

Captain SAYERS: Major Stewart's paper contains much information which I have not yet had an opportunity to digest.

I was very greatly interested in his account of the gyrorector. I recently received a description of an automatic control gear. It was written in English by a German, and I was quite unable to make head or tail of it, but it seems to have been partly a description of the gyrorector. It appears that this instrument is being used as the directing part of a purely automatic control gear. The total weight does not seem to be much more than twice the weight of the gyrorector, so that if the gyrorector was originally devised for that purpose it is not so heavy after all.

Another thing that interested me was the question of the remote drive for engine instruments. I am surprised that so little attention has been paid to electrical methods. I can quite understand that a straightforward direct current generator and voltmeter is naturally very unsatisfactory, but it is a common practice in electrical engineering to measure frequency, and an alternator is a very much simpler machine than a direct current generator. An alternator plus a frequency indicator seems a promising method of getting distant r.p.m. readings.

At present on multi-engined machines most engine instruments are on the engine mountings, and they always vibrate. Also, for some reason or another the dials of those instruments contain a large amount of information which is interesting to the manufacturers but which the pilot does not want, the dial being covered with figures and markings showing what your type of instrument is, etc., etc. When that instrument is vibrating the dial becomes a smudgy grey, and it is difficult to read it at all. I submit that those particular signs and symbols should be placed elsewhere, and the figures made blacker and clearer.

As other speakers have mentioned, instrument boards are getting congested. It is difficult to understand why it should be considered necessary to keep to the dial-shaped instruments. Edge scale instruments have long been used for electrical work and are now used for aircraft instruments in America. You can get your instruments into much less space and there is no reason why they should be more difficult to make or less accurate than the dial type.

Regarding the earth inductor compass, I understand that American makers have never suggested that this should be used without the ordinary magnetic compass in the background. The main advantage claimed for the inductor compass is that it is a zero-reading instrument. You set your instrument, and all you have to do is to see that it is reading zero. It is therefore much easier to notice a small change of course and correct it, than with the magnetic compass.

(*Communicated.*) On looking into the German automatic control gear more closely I find that I was probably wrong in believing the sensitive organs to

consist of a gyrorector. The turn indicator is apparently of a simpler type than the gyro-pendulum of the gyrorector.

Major KENNEDY: Squadron-Leader England called attention to the large number of instruments on the dashboard. One wonders whether any effort has been made to measure the degree of mental energy that is called for in a pilot to take in all these readings.

Mr. Cooke suggested that there ought to be some way of making the instruments call attention to themselves. I think that is a very good suggestion which might be amplified. Most instruments only require attention when the readings reach certain limits. It seems to me, therefore, that it should be possible to furnish those instruments with electrical contacts, and in front of the pilot—say immediately above the compass, have a line of telephone switchboard lamp signals. These might be provided with coloured glass fronts, and the colours might be associated with the particular instruments so that if the apparatus worked well the pilot would be relieved of the duty of going round the instruments, and the pressure on his mind would be considerably reduced.

Captain NYE: In the earlier part of the paper, Major Stewart called attention to the very great difficulty the instrument designer has owing to having to compensate for instrumental temperature errors. He has to compensate for temperatures varying from $-60°$C. to $+60°$C. and that is a great range. The very considerable improvements which the Royal Aircraft Establishment have been able to effect as regards temperature compensation in altimeters, for instance, is largely due to the continual use made by that Establishment of a low temperature test chamber, without which much of their success could not have been achieved. I do want to impress upon those members of the instrument trade who are here that if they want to follow up the work that Farnborough have done in the past, it is essential that they should have low temperature test chambers installed in their works.

I submit that, before they come to us with an instrument, they should know definitely that it is compensated for that big range of temperature. The success of many firms in this direction has been attained solely by the use of low temperature test chambers.

Reference has been made to the electric revolution indicator. The position with regard to this instrument is that it has been made successfully in very limited quantities, but, unfortunately, the accuracy called for is of the order of a sub-standard instrument, and you cannot expect manufacturers to produce that class of instrument in large quantities. What the manufacturers are now doing is to try and improve on what has already been accomplished. They have been given a free hand as regards the electrical characteristics of the generator and the indicator, the permissible errors have been slightly increased, and it seems that they are going to give us a really satisfactory electric revolution indicator. As soon as we have that, one of the difficulties as regards revolution indicators on engine nacelles which was mentioned by another speaker, will disappear.

Another speaker referred to the fact that, at present, pilots have to cope with a large number of miscellaneous instruments with various confused markings, and I should like to say that that matter is having attention. You must realise that at the moment old war-time instruments are still being used; that state of affairs is coming to an end and we are starting to buy new instruments, and when we do that, attention will be given to the question of reducing the matter on the dials and making the instruments easy to read.

Mr. Capon mentioned the question of a turn indicator which he said he had tested satisfactorily four or five years ago, and that, since then, no turn indicator has been adopted. This is largely because is was impossible to get the pilots to agree as to which, if any, of the various turn indicators they con-

sidered to be satisfactory, or, indeed, as to the need for a turn indicator. It was not feasible to adopt any turn indicator unless we were absolutely certain that it was satisfactory, this being largely on the grounds of economy. We now have a turn indicator, the Schilovsky-Cooke (some 150 to 200 are ordered for extended trials), which we are almost sure will be found to be satisfactory, in which case it will be adopted.

Wing-Commander T. R. CAVE-BROWNE-CAVE: I should like to know whether there has been any progress with the proximeter, by which one's actual height above ground may be determined. I remember one case in which an airship, which had been on patrol for less than 24 hours, flew into the sea at night when the altimeter showed 300 feet.

It is also important to be able to determine the height independent of the altimeter reading, because if these two heights are known the local barometric pressure can be determined. This is very valuable on a flight of considerable length.

There are, in my opinion, great advantages in the edge dial type of instrument if they could be satisfactorily made. Such instruments could be mounted close alongside each other, and their graduations and pointers be so arranged that under normal flying conditions all the pointers would lie below a horizontal line drawn across the instrument board. It would be very easy for the pilot to notice any pointer which rose above this line, and he would at once realise that something was wrong.

These instruments would probably require somewhat greater depth than is now allowed, but the great reduction of area occupied on the board might be offset against this. A more important consideration is, however, that if the instrument board is easier for the pilot to use and requires less of his attention, increased depth is probably justified.

Dr. A. P. THURSTON: We welcomed the paper as showing the vast field of invention in this branch of the science of aeronautics which still require development and which would provide rich rewards for inventive ingenuity.

He asked if any instruments have yet been devised for measuring the actual distance travelled in space, which utilise the principle of the integrating accelerometer combined with a clock.

He pointed out that the electric statoscope shows another application of the hot wire anemometer which was developed in his laboratory at East London College by Professor J. T. Morris and was described by him to this Society before the war. (AERONAUTICAL JOURNAL, July, 1924.) The principle of this instrument is the use of two wires, kept hot by the passage of an electric current, forming two arms of a Wheatstone Bridge. One of the hot wires is shielded from the air and the other is exposed freely to the air, so as to be cooled by it, thus altering its electrical resistance and throwing the bridge out of balance. This instrument is extremely sensitive and its principle may be utilised in many applications not shown by the Lecturer this evening. For instance, it can be used to indicate side-slip or to give warning of the approach of the stalling position. He had never seen the hot wire anemometer used for these purposes, but he took the opportunity of calling attention to its many applications.

Captain BYGRAVE: Several speakers have dealt with the instruments provided for the pilot's use, but no reference has yet been made to the navigational equipment. The navigator has very few instruments for his use, and usually has to carry out his duties with the aid of an altimeter which does not read true height, an air speed indicator which does not read true air speed, and a compass which does not read true direction.

Major Stewart has stated that altimeters are now accurate to 80 feet, and air speed indicators to 1 m.p.h., but it must be remembered that this is the instru-

mental or scale accuracy, and has little relation to the accuracy of their indications in aircraft.

The altimeter is a pressure operated instrument, and, therefore, does not take into account air temperature. True height is, therefore, not indicated, and in order to obtain height within 1 per cent. it is necessary for the navigator to make use of a computer which corrects the altimeter reading for air temperature. Captain Entwistle has mentioned the errors due to the horizontal pressure gradient; it does not appear possible to correct for these instrumentally, and for long flights it must normally be dealt with by forecasts or by wireless information received during the flight. Height can be obtained independently of air pressure by navigational methods; for instance, from true air speed and drift on two courses it is possible to obtain wind speed and direction, and, therefore, ground speed, when by timing the passage of a ground object through a fixed angle, height can be determined.

The errors of the air speed indicator are more serious than the altimeter; the air speed indicator makes no pretence to read true air speed, in fact, it is doubtful if it should be called an air speed indicator at all. Major Stewart has shown that the air speed indicator is instrumentally accurate to 1 m.p.h., yet at 10,000 feet it is about 15 per cent. out. This is due to the fact that the air speed indicator is pressure operated and neglects the important factor of air density.

Mr. Cooke has thrown doubt on the necessity of knowing true air speed, when the wind speed and direction are unknown. There are many ways of determining accurately the wind by observation from aircraft and by the usual two drift method, the accuracy of the wind speed obtained depends entirely on previous knowledge of air speed. Any error in air speed results in corresponding errors in the wind and the ground speed, and, therefore, in the navigation of the aircraft.

It is, therefore, necessary for the navigator to know air speed as accurately as possible. It is usual for the air speed indicator to be corrected by the use of a computer, which is set from the altimeter reading. By the use of such a computer the air speed indicator is corrected on a pressure basis instead of a density basis. It would not be so bad if the altimeter indicated true pressure, but the setting of the altimeter to zero on the ground prevents it acting as an aneroid barometer and a further source of error is introduced. Even after using the computer errors of 2 per cent. are common, and errors as large as 4 per cent. may occur. It would be a great help to the navigator if instruments could be provided to read true height and true air speed to an accuracy of 1 per cent. I, therefore, suggest that an altimeter, air speed and air temperature thermometer should be combined in one case and the movements so interconnected that true height and true air speed are indicated as accurately as possible. I should like to hear the opinion of the lecturer on the feasibility of such a combined instrument.

I notice that the anemometer type of air speed indicator is in use for research purposes. It appears that the instrument of Messrs. Stephens and Jones is an air log rather than an air speed indicator. This tempts me to ask, what has become of the air log? A satisfactory air log was produced some time ago, but it does not appear to be used. All ships are fitted with a "patent log," and it would appear that the principle is as useful to the navigators of the air as to those of the sea. The advantage of obtaining air distance from a special instrument, instead of multiplying the average air speed by time, is not only that a direct reading is obtained, but air logs can be constructed to be practically independent of air density and, therefore, much more accurate than air speed indicators. Is the failure to adopt such useful instruments because, even now, air navigation is not taken sufficiently seriously?

With regard to the "earth inductor compass," I notice that Major Stewart says that the troubles they have met with during tests should be easily overcome.

The earth inductor compass has been under development in America for many years, and it is, therefore, reasonable to conclude that every effort has been made to render this instrument as reliable as possible. The current obtained from the rotor is so minute that it is no doubt a most difficult problem to produce an indicating instrument sufficiently sensitive for the purpose, and yet robust enough to withstand aircraft vibration and landing shocks. I, therefore, concur in the opinion that has been expressed, that it would be unwise to rely exclusively on this type of compass for the navigation of aircraft.

I am glad that another speaker has referred to the question of weight reduction of aircraft instruments, because I was also much surprised that this important question was not mentioned by the lecturer. I know that a great deal of attention has been given to this matter recently and that a very considerable reduction in weight and bulk has been effected. I should like to ask Major Stewart if any further reduction is possible, and if he considers it will come by further detail improvements in design or by the employment of new principles or constructional methods.

(*Communicated.*) I notice that in the part of the paper dealing with electrical revolution indicators that Major Stewart gives a list of desirable features for these instruments. These were not given in the lecture as delivered, but as these will appear in the published paper I suggest that it should be specified that an electrical revolution indicator should not have any external field that would affect a magnetic compass fitted near by. I have a vivid recollection of a compass that persisted in pointing to a revolution indicator, quite irrespective of the heading of the aeroplane.

The CHAIRMAN: The qestion of standardisation has been referred to by many speakers, but no one seems to have touched on the possibility of getting rid of some of the instruments, such as the inclinometer, that have been standardised for many years but are not now required.

Regarding the flow meter, I think it might also have been mentioned by Mr. Capon, because you will probably remember that as long as ten years ago there was a type of flow meter produced by the Royal Aircraft Factory somewhat similar to the type which has been described this evening. I myself remember having to make a fairly long flight—2,000 miles—with that type of flow meter. On that occasion it did function well, but we had some difficulty in getting it right to start with.

With regard to the fuel gauge, I should like to ask Major Stewart whether he has considered the King Seely type which is being used in America on certain kinds of aircraft that are not normally used for aerobatics.

Regarding the earth inductor compass, Colonel Lindbergh always made it clear that he would not embark on any long flight—and certainly not on the Atlantic flight—unless he had an ordinary magneto compass as a stand-by.

REPLY TO DISCUSSION

I appreciate very much the interest which has been taken in the paper as reflected by the varied and lengthened discussion, and in replying to the many points raised, I should like, as a preliminary, to explain why so many items of interest were omitted from the paper by emphasising the second paragraph in the Introduction.

The work of instrument development in practice covers some hundreds of different items, and it is only by the most rigid selection that a paper of reasonable length can be framed. For example, the production of a low temperature low pressure chamber and the evolution of the technique of its use in instrument testing constitutes a considerable item of investigation, but space has not been found for its treatment, largely because commercial and service users of such a plant

have already been given facilities for its inspection, or have been supplied with duplicates.

Certain points of the paper, however, notably that raised by Mr. Wimperis and others regarding the explanation of the peculiar effect of the steel boss on diaphragms during temperature changes, demand elucidation.

The cause of this effect is that the differential thermal expansion of the steel and of the nickel silver stretches or compresses the disc by stress resultants in its plane.

The theoretical results of the investigation of the flat disc clearly show the stiffening effect of a stretch in the plane of the disc. A compression, of course, has an opposite effect.

Suppose that the nickel silver disc with its steel boss is cooled. The steel will contract less than the nickel silver and consequently the inner portion of the disc will be compressed. This will tend to decrease the stiffness as a capsule. The temperature effect of the modulus of elasticity, on the other hand, will tend to increase the stiffness. Hence the presence of the steel boss has a compensation effect. A brass boss would have practically no effect because the coefficient of expansion of brass is nearly the same as that of nickel silver.

This differential expansion effect is much more marked in the case of a disc whose outer edge is fixed to a stiff ring of another material, since in this case the whole disc is subject to the effect. In the case of the stiff centre piece the effect is mainly confined to the parts of the disc near the boss. By suitably choosing the materials and dimensions, a ring and disc combination may be made to possess almost any desired temperature coefficient either positive or negative.

Mr. Bramson has asked whether the attempt to make the change-over point in the double diaphragm instrument definite and adjustable is worth while. Our practice has been to make the change-over point substantially imperceptible as far as instrument readings are concerned and invariable in its incidence. This, I think, is the simpler and more straightforward method, and I may add that in our attempts at the design of new instruments, simplicity and definiteness are the two properties which are kept in mind at all stages of design. Two illustrations of this occur in the modern designs of altimeters and flow meters. In my experience I have noted that usually the complication of design leads to secondary defects which call for added complication for their removal, with the frequent result that the individual called upon to range the instrument, is faced with a well-nigh impossible task.

In reply to the same speaker's observations on the hot wire rate-of-descent meter, it is worthy of note that the instrument is designed to give the instantaneous rate of descent or the variation of the rate of descent from the mean. The instrument visualised by Mr. Bramson if it could be made accurate and substantially free from lag, would give the mean rate of descent or climb. To use such an instrument it is important to find the undisturbed air stream, and the only available place is some distance below the aircraft. A device somewhat similar in principle to that indicated by Mr. Bramson has been in use for some time, but the reading is given on a photographic record.

I regret if I have given the impression that no advance has been made with hydraulic distant reading revolution indicators. I have mentioned an instrument of continental origin, which is definitely an advance on previous designs of this type of instrument, but its behaviour is definitely less satisfactory than that of an electrical instrument of far less bulk and weight.

Mr. Capon has, like all of us concerned with the development of turning indicators, found difficulty in understanding why the re-introduction of these instruments is so long delayed.

In 1918, when cloud flying was almost a routine operation, the turning indicator was a part of the standard equipment of certain aircraft. These instruments were of the " static head " type, but useful gyroscopic turning indicators have

been in existence for some years, and have been used extensively in this and other countries. I cannot, however, agree with Squadron-Leader England in ascribing the delay to the action of pilots in refusing to countenance an instrumental check on their skill, firstly, because I do not believe that their skill is in any way likely to suffer by comparison with a turning indicator used in the correct way, and secondly, because I do not think they would reject any instrument which tended towards improving their skill. I incline to the belief that, if they dislike the indicator, it is because their daily round of work does not of necessity call for its use. My own experience has been that pilots welcome any instrument which helps them in performing their duties, but that they have a sane and healthy dislike for " gadgets " which are of no immediate and direct utility.

Squadron-Leader England has called attention to the lack of uniformity in the installation of instruments. There is almost the same lack of uniformity in the design of dashboards, and the task of those responsible for the instrument installation is by no means easy. Given a dashboard of reasonably uniform size, shape and clearance from obstructions, I have no doubt that a more uniform installation could be achieved, but the argument between the aircraft designer and those responsible for instrument installation still persists. Certainly those neat and graceful dashboards seen in foreign advertisements, wherein the instruments are depicted as occupying a small delightful oasis in a brilliant desert of polished wood or metal, indicate a wealth of useless space which would never, I believe, be tolerated by our designers. The edge-wise dial instrument with its demand for large clearances behind the dashboard, and its restricted and not too easily discernible scale finds little favour at present in this country. Instruments having edge-wise dials, and of compact form, have been made from time to time at the Royal Aircraft Establishment, and similar designs are now being made for certain of the smaller engine instruments, but any space saved will no doubt be utilised for other instruments and apparatus.

The same speaker has spoken of the complicated design of the electrical revolution indicator. I should perhaps have made it clear that these instruments have been designed solely by the electrical instrument manufacturers and in the simplest possible manner consistent with the desired accuracy of indication. The trouble is not so much apparently the complication of the instrument, as the need for devoting time and skill to the production of an expensive instrument for which there is, of necessity, a limited demand. The trouble is, in short, that electrical instrument makers can find more profitable avenues for the efforts of their most skilled workmen.

In reply to the question regarding swivelling pitot heads, there is little doubt that in performance work the correct disposition is for the static tube to be suspended below the machine. The location of the pitot tube on a swivel then gives a satisfactory reading of the instrument.

Mr. Collins, and others, have raised the question of the use of a magnetic compass in conjunction with the earth inductor compass. So far as our tests go, there is no doubt whatever that a magnetic compass must be carried and I think that Mr. Collins has tersely expressed the general opinion of pilots in the fourth paragraph of his remarks. The same speaker has referred to the question of oil flow in engines, but so far no demand has been made for an oil-flow meter for engine use, nor would such an instrument, I think, necessarily give warning of the local blocking of oil passages. Cleanliness and the maintenance of an adequate oil temperature have been relied upon to give freedom from breaking down.

Although much has been achieved in the design of altimeters, I cannot hold out much hope to Captain Entwistle that an altimeter will be devised in the near future, to indicate changes due to the horizontal variation of atmospheric pressure. An independent method of finding true height used in conjunction with an altimeter might serve, but the difficulty so far is to find such an independent method which

is simple, accurate and reliable. In practice the solution of the difficulty enunciated by Captain Entwistle would appear to be to transmit to the aeroplane the ground barometric readings.

Mr. Cooke has drawn attention to what he regards as the relative advantages of theory and empirical design in the development of instruments. I should like to assure him that our experience has been that in so far as empirical design is theoretically sound, it is good design, but even at the present time great delay and wastage is occasioned by persistent work on empirical designs which are theoretically unsound. The theoretical examination of instrument problems is undertaken to avoid unnecessary delay and to avoid waste of public funds, and so far the results achieved have justified the means adopted. It is in the effort to make this clear that so much space has been given to the theoretical aspects of the various problems.

Mr. Cooke has expressed alarm at the weight of the gyrorector. The instrument has been described in detail as likely to be of particular interest to designers of gyroscopic instruments for use on aircraft. It is not a standard instrument on British aircraft.

I must apologise to Mr. Cooke and others for not emphasising the reductions in weight and bulk that have been carried out recently, but it was felt that space did not permit of this amplification of the subject matter of the paper. The weight of the Verey pistol as well as all other items of aeroplane equipment was reviewed about a year ago.

I think everyone who has followed Mr. Cooke's efforts on the Schilovsky-Cooke turning indicator will appreciate the value of his work, but I do not agree that all the earlier types of turning indicator failed in the laboratory. We are all aware of the great utility of certain established forms of turning indicator, notably the Reid control indicator which has found such favour among civilian pilots. Again, I find it hard to follow this speaker's argument against the "canting" of the horizon line of the gyrorector. He states the "cross arm cants to port to show that the machine is canting to starboard." Surely the natural horizon appears to do the same thing, and in the absence of the visible horizon, which is the condition under which the instrument is really useful, the artificial horizon line serves as an indication of the relative attitude between the machine axis and the natural horizon. In short, I fear the pilot would be considerably "harassed" if the natural horizon did not appear to do what Mr. Cooke complains that the artificial horizon does.

The suggestion that pressure gauges should indicate by a coloured light when "something is wrong," is hardly one to recommend itself to practical flying folk. Assuming that the danger point of pressure were, say, 25lbs., and that the light came on, in consequence of the pressure falling to 24lbs., the pilot would be left without any indication whatever of how much "something was wrong," and he would have to decide whether to ignore the warning or to attempt a forced landing.

The purpose of the flexible drive referred to is to produce an indication at a distance without having to transmit considerable power. The range of lateral movement of the shaft is not necessarily limited to a very small amount.

The length of the scale of the fuel flow meter described is limited, and openness of scale is required over the useful range. Instruments for indicating smaller flows are being made.

Captain Sayers has, I think, made a valuable point in dealing with the very pertinent aspect of the attitude indicator in relation to automatic control gear. There seems little doubt that engineers in foreign countries are devoting attention to the application of the gyroscopic devices to control systems, and if any appliances I have referred to serve to stimulate invention in this country, then perhaps we may all forgive such shortcomings as weight.

It is only fair, I think, to those electrical instrument makers in this country, who have spent considerable time and money in developing electrical revolution indicators, to say that they have not limited their investigations to the generator-voltmeter system. As I have mentioned in the paper, entirely different systems have been tried, and the frequency meter method advocated by Captain Sayers has been under investigation for some time with promising results.

I am glad that Captain Nye has emphasised again the need of the low temperature, low pressure chamber in instrument testing. Admittedly, the present cost of such a chamber is high, and the working expenses, when liquid air is the cooling agent, are not small. A modified form of chamber using carbon dioxide as the cooling agent has, however, been designed and constructed at Farnborough and the working expenses have been considerably diminished. It is hoped in the near future that greater facilities will be afforded for the extended use of such apparatus.

Wing-Commander Cave-Browne-Cave has asked for information regarding the progress of the proximeter. He presumably refers to that device based on the change in electrostatic capacity as the aircraft approaches or recedes from the earth. As a result of considerable work in the past it has been found that, in the present state of the art, any change of capacity of an apparatus attached to the machine is so small as to render the device unworkable in the air above heights of a few feet.

Other methods of finding heights independently of the altimeter are under test, but no definite information regarding their utility is yet available.

Dr. Thurston, while expressing his laudable professional hope, calls attention to another wide area of invention, namely, the calculation of distance travelled from the integrations of acceleration. I fear that the exploration of this field of work is unlikely to prove profitable to all parties, for so far it is not possible to promise that correct estimations of distance are likely to be so obtained over more than very short time intervals.

Captain Bygrave has voiced the lamentations of the navigator in his remarks, yet those instruments for which he seeks are not hard to find. The combined altimeter and computer was a standard instrument during the war period, and altimeters of the Spiral and Iris dial type can be set for air temperature—automatically—if so desired. Air speed indicators corrected for density changes have been made and have not been called for until recently by navigators. New forms are under development, and one type at least is in use abroad.

Provided that such an instrument, as Captain Bygrave suggests, for indicating true height and true air speed is demanded, there should be no great difficulty in supplying it after a reasonable period. So far the design of such special instruments has lagged because no sustained demand has arisen. The same speaker seeks information regarding the air log. Some time ago an attempt was made to interest navigators in this instrument by sending for trial two tried examples, one of British origin and one of American origin, but no demand was made for further instruments.

I agree with Captain Bygrave that while engine and flying instruments and observational appliances have made marked progress, little has been done of recent years to improve navigational instruments other than the compass, and I feel that this state of affairs is partly explained by the relatively few demands made by navigators in comparison with those made by pilots and observers.

There is a lively prospect that considerable saving in the weight and bulk of instruments may be achieved in the future, but I have refrained in the paper from making anything in the nature of a forecast. Apart from the re-designing of instruments in their present form, experiments are being made with silica manometers, and these experiments indicate an astonishing range of movement and freedom from lag. If such manometers can be incorporated in aircraft instruments

the time may come when instrument designers may enjoy an existence unharassed by the exhortations of the weight whittlers.

In reply to Colonel the Master of Sempill, the whole question of the utility of the instruments normally carried on the dashboard was reviewed about eighteen months ago, and the decision arrived at was that none of the instruments could be dispensed with. The dashboard lighting system is, however, being completely modified.

The flow meters hitherto constructed, either at the Royal Aircraft Establishment or elsewhere, have been, as indicated by the Chairman, erratic and often incorrect in action.

It has, however, been possible to select from a sufficient number, one which would be approximately correct although the type itself was open to objection on the ground of inconsistency of reading.

Before the design of the flow meter described in the paper was started, a critical review was made of all known types, and an attempt has been made in the present design to avoid the defects inherent in the earlier types.

An examination of the King Seely type of fuel depth gauge will be carried out. It is unlikely that any instrument likely to be deranged through aerobatics would be regarded as satisfactory.

In conclusion, I should like to express my thanks for the interest which has been taken in the paper and particularly to those speakers who have, by their criticism and observations, thrown light on the needs of those whose duty or pleasure lies in the great airway.

PROCEEDINGS

FIFTH MEETING, SECOND HALF, 63RD SESSION

The Fifth Meeting of the Second Half of the 63rd Session of the Royal Aeronautical Society, with which is incorporated the Institution of Aeronautical Engineers, was held in the Theatre of the Royal Society of Arts, 18, John Street, Adelphi, W.C.2, on Thursday, February 16th, 1928, when Dr. G. P. Douglas, D.Sc., A.F.R.Ae.S., read his paper on "Experiments on Model Airscrews at High Tip Speeds." Colonel the Master of Sempill (President of the Society) was in the chair.

The CHAIRMAN, introducing Dr. Douglas, said that the work upon which he had been engaged for some years past was of the greatest importance, and he believed that in this particular line of research we could claim to be in advance of others. The result of the researches undertaken by Dr. Douglas would probably make themselves felt during the following month, when the Supermarine S5 would go out to do what we all felt it would do without difficulty, namely, capture the world's speed record.

EXPERIMENTS ON MODEL AIRSCREWS AT HIGH TIP SPEEDS

BY G. P. DOUGLAS, M.C., D.SC.

The object of this paper is to give the Society an account of the methods which are used at the Royal Aircraft Establishment to deduce the variations which occur in the lift, drag and incidence relationship of the blade sections of model airscrews when the tip speed is increased up to and beyond the velocity of sound. The investigation of the properties of the model airscrews has brought to light the changes in detail which occur in the characteristics of these airscrews as the tip speed is increased from low speeds to these high values, and these may interest the Society. Most of the results of the investigations have been published as the work was carried on and it is profitable to review the earlier work in view of our further knowledge.

I have to thank the Air Ministry for permission to read this paper, but should state that any conclusions I may express represent only my personal views on the subject.

The numbers in the footnotes refer to the list of references given at the end of the paper.

The earlier work was carried out in collaboration with the head of my department, Mr. McKinnon Wood, M.B.E., B.A. The subsequent investigation of torque grading methods was in collaboration with Mr. Coombes, B.Sc., and the later tests in collaboration with Mr. Perring, R.N.C. Mr. Lynam undertook the design of the model airscrews. The turbine used to drive the airscrew was suggested by Mr. Salmon, who carried out the original design. I have to thank Mr. McKinnon Wood and Mr. Glauert for their valuable suggestions and advice throughout the work.

1 Historical Introduction

The beginning of the high tip speed experiments at the Royal Aircraft Establishment was marked by a rather striking demonstration. A fine pitch airscrew, 9ft. in diameter, with rather thick blade sections of the conventional

type, was mounted on the spinning tower and rotated by the electric motor at gradually increasing speed. When the tip speed was 800 ft./sec. the flow was of the normal type and the slipstream was sufficiently powerful to make it difficult to stand in the stream 10 ft. from the airscrew. The speed of rotation of the airscrew was increased and as the tip speed approached the velocity of sound (say 1120 ft./sec.) the slip stream rapidly diminished and vanished completely when the blade tip attained the speed of sound. The disappearance of the slipstream showed that the thrust must have become practically zero but the power required to drive the airscrew continued to increase. Our more recent tests furnish an explanation of this, but at the time it drew attention to the need for further knowledge regarding the properties of airscrews running at high tip speeds and it was decided to extend the tests to flight conditions.

A specially designed airscrew was fitted to a D.H.9A aeroplane with a geared Napier Lion engine with gearing altered to give the equivalent of direct drive and a few thrust measurements made at tip speed equal to the velocity of sound. The conditions were not such as to repeat the striking effects found on the spinning tower and it was decided to carry out a series of model experiments where the conditions would be under more convenient control.

2 *Use of Models at High Speeds*

The thrust and torque of an airscrew are conveniently expressed by non-dimensional coefficients

$$k_T = T/\rho n^2 D^4 \text{ and } k_Q = Q/\rho n^2 D^5$$

which are functions of the advance per revolution $J = V/nD$.

Variation of the function k_T and k_Q for an airscrew of given shape with variations in size, speed, density and viscosity is expected to be a function of the quantity LV/ν, usually called the Reynolds number, and also of the ratio of the velocity of motion through the fluid to the velocity of sound in the fluid which we denote by v/a. The v/a effect is expected to be negligible at low speeds and to become important as the velocity approaches that of sound. Some idea of the speed at which this effect becomes important may be obtained from the table below, which shows how the absolute pressure (p) at the stagnation point on a blade section increases with speed. The ratio of the theoretical value (p) to the value in the undisturbed fluid (p_0) is given. For normal flying conditions p/p_0 is the stagnation pressure in atmospheres.

Velocity.	v/a	0.2	0.4	0.6	0.8	1.0
	ft./sec. at 15°C.	224	448	672	896	1120
Stagnation pressure ratio p/p_0 ...		1.03	1.12	1.28	1.52	1.89

At high speeds the Reynolds number effect is rather uncertain and this must be remembered in using the model tests to estimate full-scale values. At low speeds the conventional airscrew sections have been tested as aerofoils over the full range of Reynolds number from that of our present model tests to full-scale value and show only minor variations over the working incidence range and these variations decrease with increasing Reynolds numbers. The v/a and Reynolds number effects are not independent and although the flow pattern round an aerofoil may be stable at low speeds over a wide range of Reynolds number, there is always the possibility that at higher speeds the flow may be modified by compressibility to an unstable state varying with Reynolds number. The model must be tested at the correct v/a and its scale varied to find to what extent the coefficients are independent of Reynolds number.

The blades of an airscrew running at high speeds may distort appreciably under load in which case, if E', ρ', V' are the elasticity, density and velocity of the blade, the thrust and torque coefficients depend on $E'/\rho' V'^2$ and ρ/ρ' in addition to LV/ν, v/a and J. A model and a full-scale airscrew made of the same material and running under similar conditions would thus distort to the same extent when running at the same tip speed.

Velocity of Sound

The velocity of sound in air, denoted by "a" in this paper, is 1,120 ft./sec. under standard ground level conditions (temp. 15°C.) and varies as the square root of the absolute temperature. Thus under standard atmospheric conditions it would be 1,080 ft./sec. at 10,000 ft. (temp. −4.8°C.) and 1,040 ft./sec. at 20,000 ft. (temp. −24.6°C.).

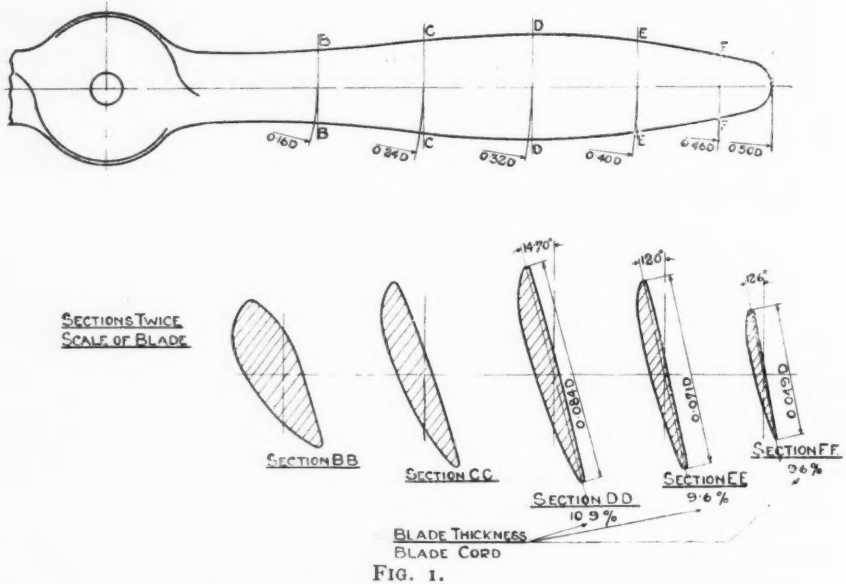

FIG. 1.

General Arrangement of Wood Airscrews used for Preliminary Tests. Model Airscrews 2ft. Diameter.

3 General Outline of Experiments

The experiments I propose to describe were made to obtain some information about the characteristic of airscrews when running at tip speeds up to and beyond the velocity of sound. In the earlier work we were interested in the general nature of the changes which take place at these high speeds and methods had to be devised by which these changes could be accurately measured and could be analysed. In the work now proceeding we are interested in obtaining data to enable the designer to predict the torque and efficiency of airscrews with blade sections of conventional type and to see what modification in the shape of these sections will reduce the serious loss of efficiency which occurs.

The main scheme of the investigation was as follows:—

Apparatus was designed by which model airscrews could be rotated over a wide range of tip speed up to 1.3 times the velocity of sound while the variation

of the thrust given by the airscrew and the torque absorbed was measured. To explain the observed variations, methods were found of showing how the thrust and torque distribution along the blades varied over this range of tip speed. Also the blade twist was measured. From these measurements the variations with speed of the lift and drag coefficients of the blade sections were deduced. The present paper gives a description of the methods and a few typical examples of the results obtained.

The tests have been made in the No. 2 7 ft. wind tunnel at the Royal Aircraft Establishment. This tunnel has a speed range from 25 to nearly 100 miles/hour, so that the action of any model airscrew could be investigated over a reasonable range of V/nD. The airscrews were two feet in diameter. Fig. 1 shows the airscrew used for the earlier tests. It has two blades of symmetrical plan form and a small forward tilt. It was made of black American walnut and proved to be of satisfactory strength for tip speeds up to 1,200 ft./sec. The blade twist under running conditions sometimes exceeded 2° and the blades were liable to

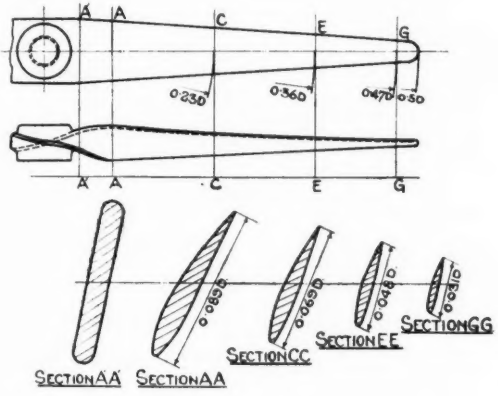

FIG. 2.

General Arrangement of Steel Airscrew Blades. Model Airscrews 2ft. Diameter.

warp slightly between tests. On this account the blades used for the later tests were modified in shape and made of 65-ton steel. Fig. 2 shows a typical airscrew. Each blade is of the same aerofoil section over its working portion. The chord of the section diminishes as the radius increases and the design allows the blades to be first roughly planed to section and then twisted to any required blade angle—a process resulting in a very robust airscrew upon which a minimum of bench work is necessary. All the steel airscrews mentioned in this lecture and used to investigate the properties of the various blade sections were of this type over the working portion of their blades; they all had exactly this plan form and only the blade angles were varied. To obtain small angles of incidence at high speeds at the comparatively low wind tunnel speed available, the airscrews have to be of fine pitch. The airscrew efficiency is consequently rather low and its variation with speed large. Apart, however, from the limitation of tunnel speed the drag coefficients of the blade sections can only be deduced with any accuracy from low pitch airscrews in which the drag forms a fair proportion of the torque. Fig. 3 shows some of the blade sections which have been tested.

4 *The Turbine and Thrust and Torque Apparatus*

Various methods were considered of driving the airscrew at the required speed and an air turbine appeared to be the simplest proposition. Fig. 4 shows the original air turbine and Fig. 5 the "cleaned up" form now in use. It develops about 60 h.p. Air is led in underneath the turbine and passes through the nozzles to the rotor and is discharged axially. It is desirable that the turbine should be as far as possible a solid revolution and that any necessary projections, such as the air intake pipe, should be small and sufficiently far back to have negligible interference on the flow through the airscrew disc.

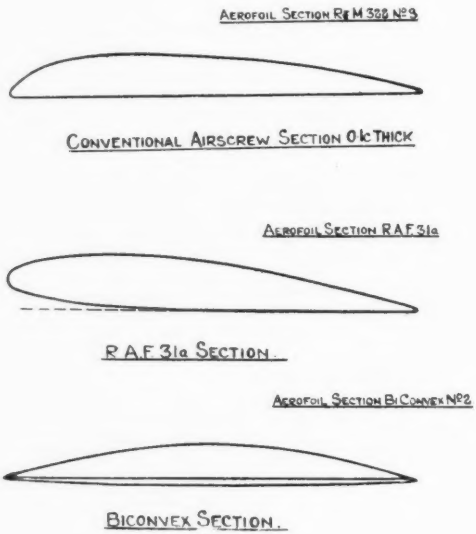
AEROFOIL SECTION R&M 328 Nº3
CONVENTIONAL AIRSCREW SECTION 0·1c THICK
AEROFOIL SECTION R.A.F. 31a
R.A.F. 31a SECTION.
AEROFOIL SECTION BI CONVEX Nº2
BICONVEX SECTION.

FIG. 3.

Details of Aerofoil Sections Tested at High Speeds.

Fig. 6 shows the general arrangement of the turbine. The shaft is carried well forward so that the air intake pipe may not interfere with the flow at the airscrew and the pipe is made of streamline section. The labyrinths *XX* and *YY* are used to prevent air leakage.

The torque is measured by reaction. The turbine is carried on anti-friction rollers at *AA* and on a ball-bearing at *D*. It is free to rotate between stops formed by electric contacts, and an arm attached to the rear of this rotating portion connects to a spring balance under the floor of the tunnel. Readings of the spring balance are taken when the turbine floats freely between the contacts.

No ball-bearing system used for small rocking movements will last indefinitely under vibration as the balls tend to pit and form flats; by the end of a series of tests the falling off in sensitivity is just noticeable and the surfaces are examined before the next series.

As the torque of the airscrew is being measured by its reaction on the turbine casing it is necessary to ensure that the torque measured is entirely due to the airscrew. The slipstream from the airscrew itself must not apply a torque to the casing. On this account it is arranged that the slipstream has the minimum contact with the casing and where contact is made the surface is that of a solid

of revolution about the torque axis and is smooth and free from projections. It is very important that the compressed air introduced into the casing should have no angular momentum about the torque axis and also that the exhaust should be discharged without angular momentum about the torque axis. The exhaust is discharged axially and to ensure that it had no rotational momentum a series of

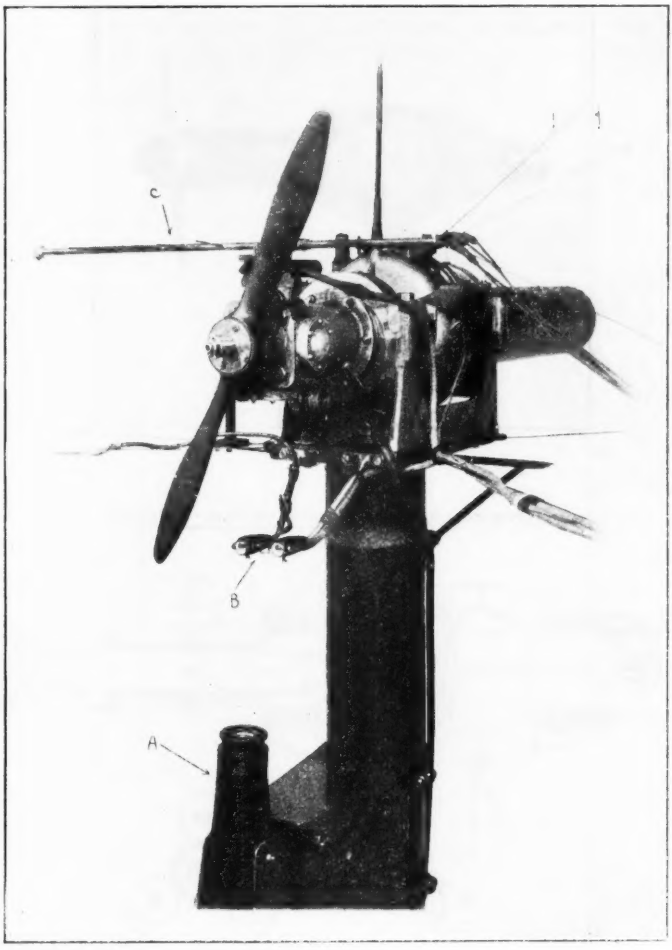

FIG. 4.

baffle plates were fitted in the exhaust tube. The number of baffles in this tube was increased until the addition of further baffles made no difference to the torque reading.

The introduction of the compressed air was the most difficult problem and for our early experiments a mercury seal was used. The constructional difficulties were considerable as the clearances had to be small and to prevent action by

the mercury the seal had to be made of steel and all joints welded. To maintain a pressure of 35 lbs./sq. in. a head of 80 inches of mercury was required and it was found most convenient to have two concentric seals in series each giving a 40 inch head. Petrol was used to connect the inner

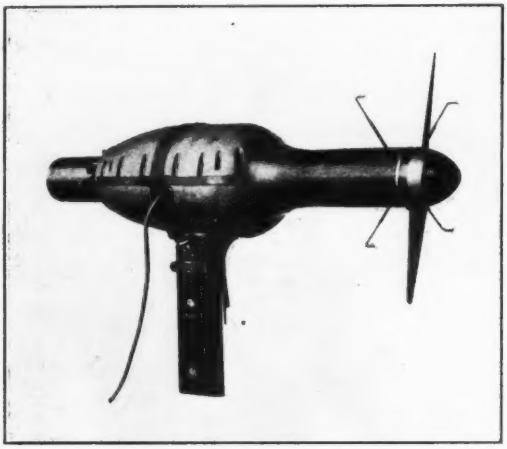

FIG. 5.

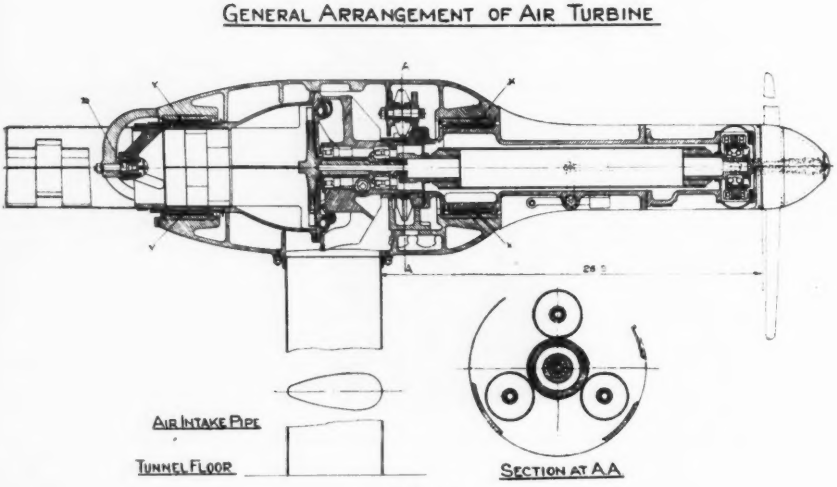

FIG. 6.

and outer seals. The seal worked very well, but required great care in use as, if the pressure were applied too rapidly, it blew all the mercury out of the seal. On one occasion when this happened we noticed that the absence of the mercury made surprisingly little difference to the power given by the turbine. Apparently the loss in head of the air going round the various corners

was sufficient to maintain the pressure with slight leakage. Accordingly, when an opportunity occurred of redesigning the turbine, we incorporated the labyrinth scheme shown. The absence of angular momentum at entry was checked by clamping the airscrew to the casing so that it could not rotate and noting that there was no difference in the torque reading when the compressed air was turned on.

To measure thrust the shaft carrying the airscrew is mounted so that it is free to move axially independent of the shaft carrying the rotor. The torque is transmitted from the one shaft to the other by means of grooves filled with balls. A linkage connects the airscrew shaft to a balance under the tunnel.

In order to determine the thrust contributed by the blades apart from the thrust introduced by forces acting on the boss and spinner, measurements were made of the pressures over the spinner and over the boss disc at the rear of the airscrew. The readings at the rear of the boss were taken continuously during the experiments, but for the pressure distribution over the nose of the spinner special experiments were made. A dummy spinner carried in place of the ordinary revolving spinner was held in a fixed position by a tube from the tunnel floor, and down this tube passed the pressure piping which linked up the gauge glasses of a manometer with a series of holes in the spinner. The measured thrust of the airscrew can be corrected for the spinner drag, calculated from these experiments.

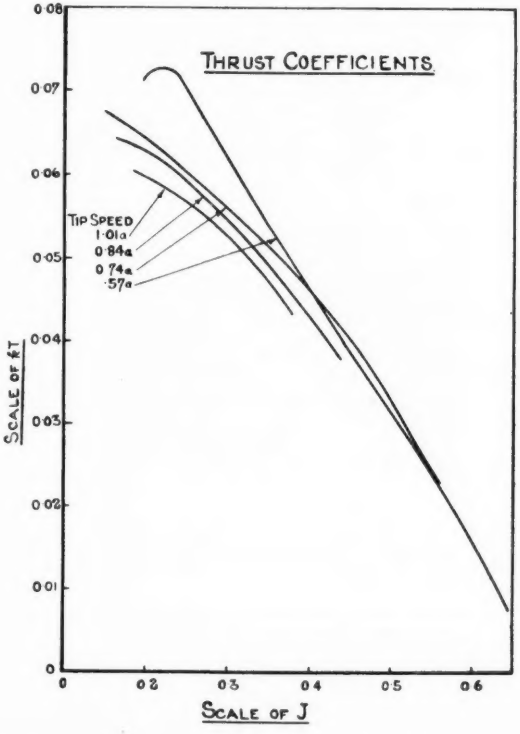

FIG. 7.

Airscrew with Conventional Blade Section of Thickness =0.1 Chord.

The spinner is of a shape which could not readily be applied to aeroplane designs, but it is of interest to note that the pressure over the front part of this spinner does not reduce the thrust by any appreciable amount and may even assist it.

The following figures show the results obtained for a typical airscrew when tested on this apparatus. The airscrew was one of the steel type shown in Fig. 2 and the blade sections were formed of typical airscrew section with flat under surface. The maximum thickness of the section was 0.1 of the chord. Fig. 7 shows how the thrust coefficient varies with speed. The larger thrust coefficients fall off continuously with increase of speed, but the medium values increase slightly before falling off. (The actual thrust, of course, continues to rise and the falling off in the values of the coefficients indicates that the thrust is increasing less rapidly than the square of the speed.) Fig. 8 shows the steady increase in

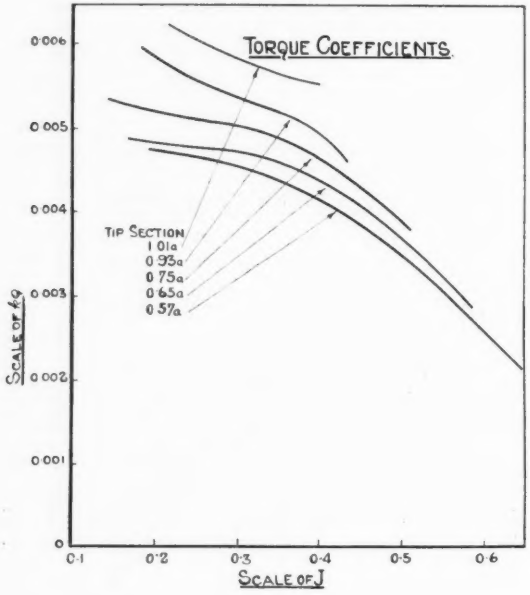

FIG. 8.

the torque coefficients as the speed is increased. From these thrust and torque values the efficiency has been estimated and Fig. 9 shows how the efficiency of this airscrew falls off with speed.

Fig. 10 shows rather more conveniently this fall off in efficiency at $J=0.35$ and the results are compared with those for two other airscrews of similar pitch tested on this apparatus. One was the wood airscrew shown in Fig. 1, the second a steel airscrew with blades of R.A.F. 31a section (Joukowski type, max. thickness 0.127 of chord). The general fall off in efficiency with increase of tip speed is similar for all the airscrews although the wooden airscrew with its wide blade suffers least. These are merely typical curves for complete airscrews and must not be used to compare the actual merits of the blade sections.

In the figure are included two curves which give a rough estimate* of what the efficiency of the first airscrew would have been if the blades had been modified to give the same thrust at a higher J, while the mean value of $\tan\gamma$,

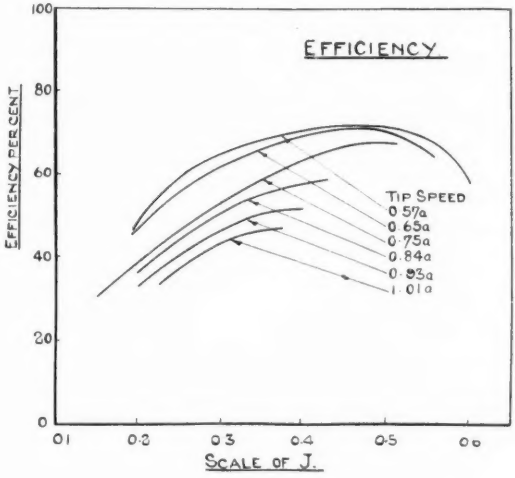

FIG. 9.

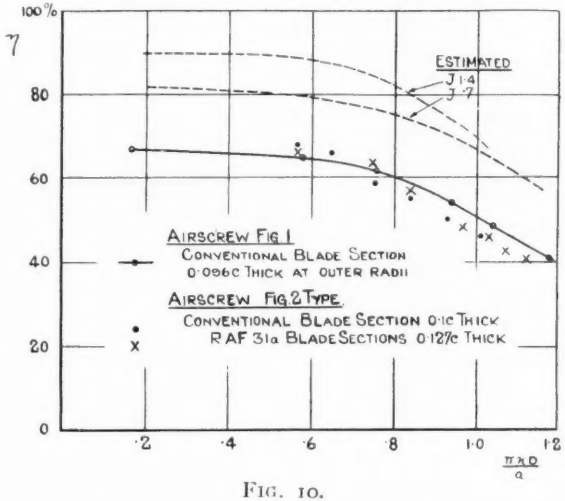

FIG. 10.

Variation of Efficiency with Tip Speed for Three Airscrews of $P/D=0.7$ at $J=0.35$.

* The equations of § 12 are used. A mean value of the inflow is taken at each J and the mean value of tan over the working portion of the blades is assumed constant. At a given tip speed the average air velocity relative to the blade increases with increase of J. The increase varies with the radius, and the speed at 0.7 of the tip radius is taken as a mean.

i.e., the ratio of the drag to lift loading along the blade, remained unaltered. They give some idea of the type of loss which would occur on an airscrew of normal pitch running at these tip speeds. At $J=0.35$ the tip speed relative to the air is practically the same as the rotational component, but at $J=1.4$ it may be 10 per cent. higher.

The changes in the thrust and torque taking place at high speeds presumably occurred to the greatest extent at the outer portion of the blade where the velocity was highest and the effects were partly masked by the remainder of the blade behaving in a more normal manner. To obtain detailed information about these changes we required to know the thrust distribution along the blade, the torque distribution along the blade, and the extent to which the blade twisted.

5 *Thrust Distribution*

The pitot tube method originally used by Sir T. E. Stanton, F.R.S., offers a very convenient means of obtaining the thrust distribution. The area in which the airscrew is rotating is regarded as a disc of discontinuous pressure, the

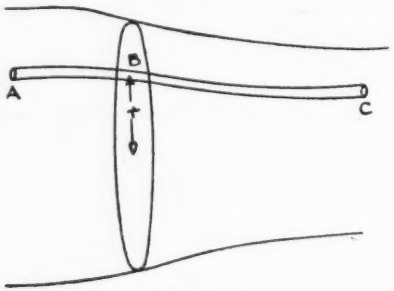

FIG. 11.

intensity varying with radius. For any stream tube passing through the disc the total head at a point A ahead of the airscrew will be equal to the total head at C behind the airscrew plus the pressure energy added at the disc and a small correction, usually negligible, for the rotation of the air behind the airscrew. A pitot tube will measure the total energy at any point along the stream tube so that the difference in pressure, p, between pitot tubes set up successively at A and C will measure the pressure difference produced by the thrust of the blade elements at the radius at which the stream tube crosses the disc. If this radius be r

$$dT = 2\pi r p dr$$

or since $T = k_T \rho n^2 D^4$ and $x = 2r/D$ we can express this non-dimensionally in the form

$$(dk_T/dx) = (\pi r p/\rho n^2 D^3) = (\pi x p/2\rho n^2 D^2)$$

The position of the front pitot tube is not important as the pitot pressure should be constant in front of the airscrew, but it is necessary to know the exact radius at which the stream tube which reached the rear pitot passed through the airscrew disc, especially if the pressure difference is varying rapidly with radius. On this account small diameter pitot tubes were used and mounted close behind the blades so that the radius at C could not differ appreciably from that at B. Prior to the present work this method had only been used on an airscrew running at low speed. In considering its application to the high speed airscrew of the present tests it must be remembered that although the blade may pass the pitot at a high velocity, the mean velocity of the air relative to the pitot never

exceeded, say, 200 ft./sec. The accuracy of the method can be checked by comparing the direct measured thrust with the integrated value from the pitot readings.

Fig. 12 shows four pitot-yawmeter tubes in position, each at a different radius ready for a determination of thrust grading. They are connected to a multiple

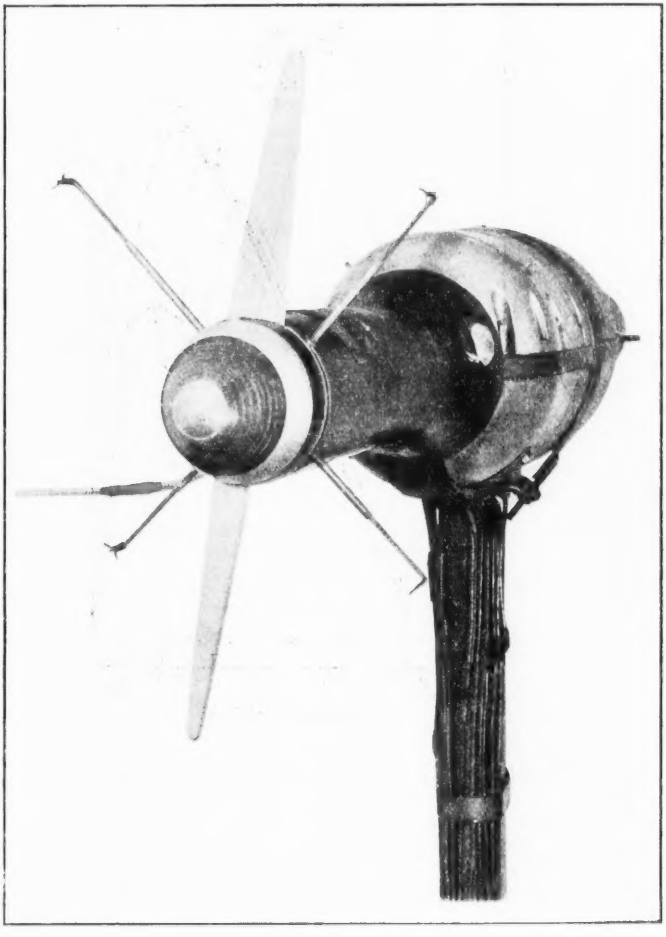

FIG. 12.

manometer filled with alcohol and photographic records are taken of the levels of the liquid columns, the air speed and the tacheometer reading. The most complete pitot exploration was made on a steel airscrew as in Fig. 2 with blades of R.A.F. 31a section. Eight pitot tubes were used in this case. Fig. 13 shows how the thrust coefficient is distributed along the blade at $J=0.25$ and is fairly typical of the steel airscrews we have tested. As the speed is increased the curves tend to rise at the inner radii and stall from the tips inwards, collapsing to a lower

value. The broken line shows the thrust distribution calculated by the Glauert theory using data obtained from an ordinary wind tunnel test of an aerofoil made to this blade section, and shows that ordinary wind tunnel data becomes more and more unsuitable for the prediction of thrust distribution as the speed

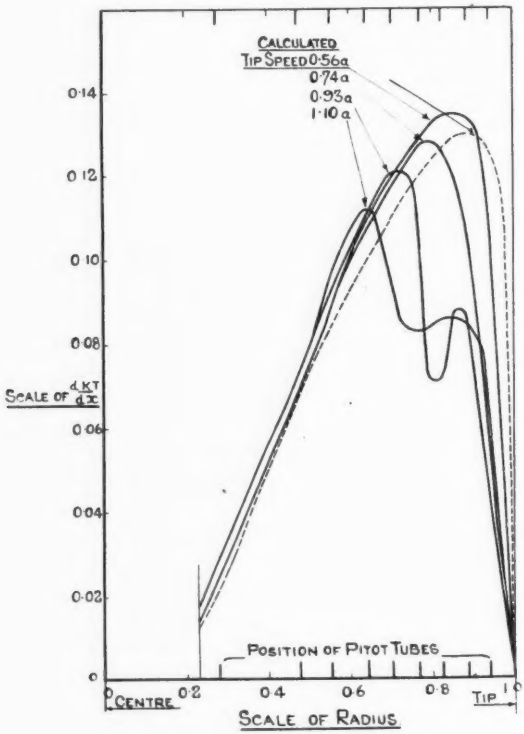

FIG. 13.

Thrust Grading Curves R.A.F. 31a Airscrew.
$J = 0.25$.

increases. The blades of this airscrew were not twisting appreciably so the changes are due to aerodynamic causes. The way in which the tip sections take less and less of their share of the thrust as the speed increases is particularly marked.

Fig. 14 shows the comparison of the integrated values of the thrust of this airscrew with the directly measured values. The general agreement is good over the complete range of tip speed investigated.

6 *Torque Distribution*

It is possible to deduce the approximate values of the lift coefficients of the blade sections from thrust grading curves such as have been shown and to show how the lift coefficients vary with speed. To find the corresponding variation of the drag coefficients the torque grading must be known and the following

paragraphs describe a few of the experiments made to find a satisfactory method of measurement.

The torque of an airscrew must be equal to the moment of the rotational momentum generated in the slipstream in unit time.

For an elementary annulus, if dm is the mass of air passing through the annulus in unit time

$$\begin{aligned} dQ &= \omega r^2 dm \\ &= (\omega r^2)\,(\rho 2\pi r dr U) \\ &= 2\pi\rho V U r^2 dr \end{aligned}$$

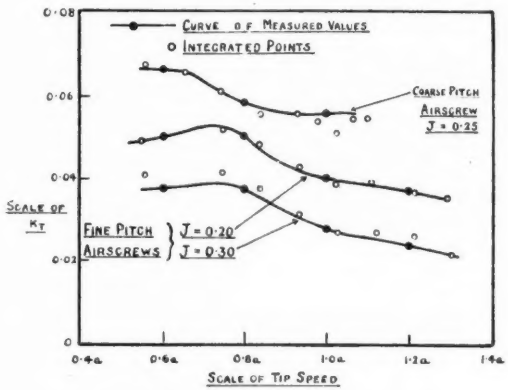

FIG. 14.

Comparison of Measured and Integrated Thrust. R.A.F. 31a Section Airscrews.

FIG. 15.

where U is the axial velocity and V is the tangential velocity. The problem is to measure UV. If W is the resultant velocity and ψ is the angle of yaw

$$\begin{aligned} VU &= W\cos\psi W\sin\psi \\ &= \tfrac{1}{2}W^2\sin 2\psi \\ Q &= \pi\rho\int W^2\sin 2\psi r^2 dr \end{aligned}$$

7 *The Flow Behind an Airscrew*

Fig. 16 gives an estimate of the variation of velocity and yaw which would have been experienced by a yawmeter placed behind an element of the airscrew blade which had the same flow pattern around it as that measured for the infinite

aspect ratio aerofoil described in R. & M. 989. The diagrams of velocity and pitch given in that report were regarded as a development of the flow in the annulus containing the blade section. Sections were taken along lines making a given angle ϕ with the undisturbed wind and passing at different distances behind the trailing edge of the aerofoil. The direction and magnitude of the resultant velocity relative to a stationary yawmeter were then obtained by vector addition. The diagrams show the variations while the blade travels through 180°. The most interesting feature is the very great variation of yaw throughout

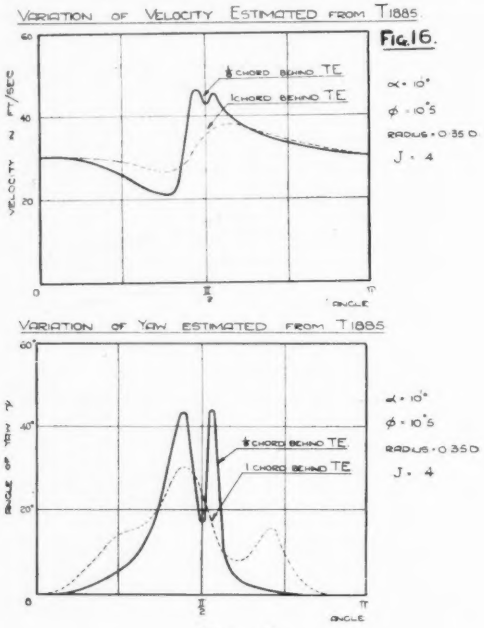

FIG. 16.

the cycle. The lift coefficient of the aerofoil was about 0.75, which is higher than would normally be obtained from an airscrew blade, so the diagram probably exaggerates the yaw variation likely to be encountered behind an actual airscrew. On the other hand, the average value of ψ is only 8° and mean values of ψ up to 7° have been measured behind an actual airscrew.

The valley between the two "peaks" in the lower diagram is where the yawmeter is passing through the highly turbulent wake coming from the trailing edge of the aerofoil. If variation of profile drag with speed is to be determined successfully it must be necessary to measure correctly the angular momentum in this wake.

8 *Measurement of Angular Momentum*

To measure the angular momentum we can measure either

(1) The difference in pressure between the limbs of a fixed yawmeter whose calibration is known, or

(2) Rotate the yawmeter until the pressure difference between the limbs is zero, so determining the angle of yaw and then, using the yawmeter as a pressure head, determine the velocity separately.

If we use the first method it is necessary to use a yawmeter which has a calibration such that its pressure difference, p, varies as $\frac{1}{2}W^2 \sin 2\psi$ over the range of ψ which we are likely to encounter. Since the instantaneous pressure gives the angular momentum at any instant, the mean pressure will give the mean angular momentum. Mr. Glauert has shown* that the second method will also give the correct result in periodic flow provided that the pressure head used has a calibration such that the pressure difference, p', varies as $W^2 \cos 2\psi$.

Pitot tubes do not give pressures proportional to $W^2 \cos 2\psi$, but give a much more constant reading up to $\psi = 20°$. A velocity head either of the pitot-static or pitot-yawmeter type diverges still more from the $W^2 \cos 2\psi$ relationship. For this reason the second method appeared to be impracticable and the investigation was confined to the first method. The first method is also very suitable for giving a photographic record of the observations.

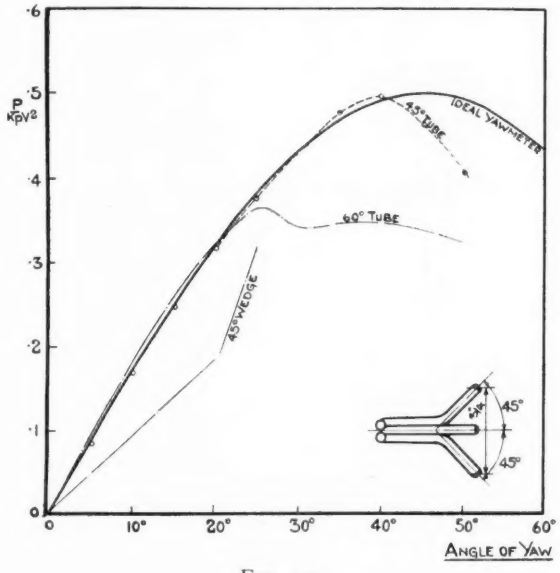

FIG. 17.

Typical Yawmeter Calibration Curves.

9 *The Ideal Yawmeter*

The ideal yawmeter for the method should possess the following features:—

(*a*) A calibration such that P varies as $\frac{1}{2}W^2 \sin 2\psi$.
(*b*) The calibration should hold good up to large angles of yaw (40° if possible).
(*c*) Freedom from scale effect.
(*d*) A calibration unaltered by turbulence.
(*e*) As small an interference on the flow in which it is placed as possible.

After a number of trials a yawmeter made up of two pitot tubes set at $\pm 45°$ to the centre line was chosen as the most promising instrument. This angle was arrived at from tests of a single pitot tube over a large range of yaw, two

* R. & M. 992.

other dummy tubes being present for interference. Calibration curves for various included angles were deduced, and the approximate best angle found. One or two actual trials then sufficed to fix the most suitable angle. Reference to Fig. 17 will show how nearly the calibration of the 45° yawmeter approaches the ideal. At 40° the calibration breaks down, but its range was considered sufficient. On

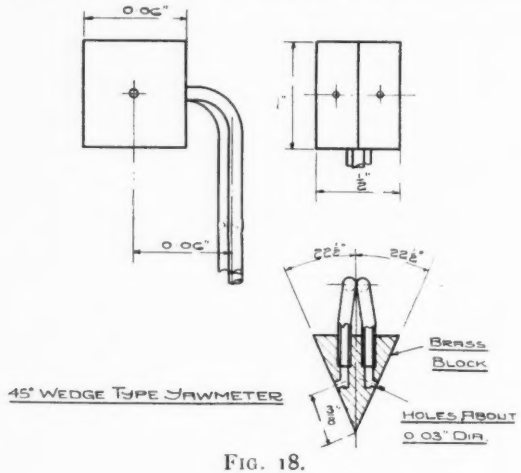

FIG. 18.

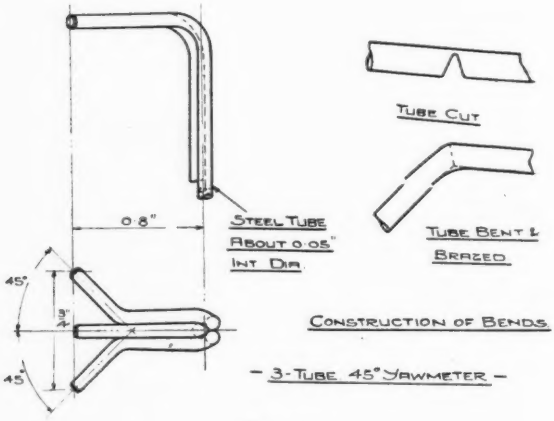

FIG. 19.

the same figure are shown the calibration curves for a similar yawmeter with tubes set at $\pm 60°$, and for a wedge-shaped yawmeter of face angle 45° (Fig. 18). The 60° yawmeter is good up to 25°, but it has not as great a range as the 45° yawmeter. The wedge-shaped yawmeter was designed to be free from scale effect, and actually none was observed between 40 and 80 f.p.s., but its calibration is clearly of a quite unsuitable type.

To cut down interference, it was necessary to make the yawmeter as small and as neat as possible, and this was also desirable on account of the periodic

nature of the flow in the slipstream, which made any separation of the yawmeter tubes a source of error. It was found that the calibration was sensitive to slight errors in manufacture, and in order to have as much straight tube as possible for setting the angles correctly, a method of mitreing the tubes instead of bending them was adopted. The sketch (Fig. 19) makes the construction clear. The yawmeter was made of steel tube, assembled and trued up in a jig, the tube ends being faced and bevelled by machine. This method of manufacture, though calling for good workmanship, was found to be reasonably satisfactory and in the subsequent work a mean calibration was used for all the yawmeters. The actual calibration constants showed slightly erratic minor variations with speed usually within 1 per cent. of the mean, although variations up to 3 per cent. were found.

It will be noted that a central pitot tube has been incorporated so that the total head can be measured simultaneously; also the three-tube type gave a better calibration than the two-tube type.

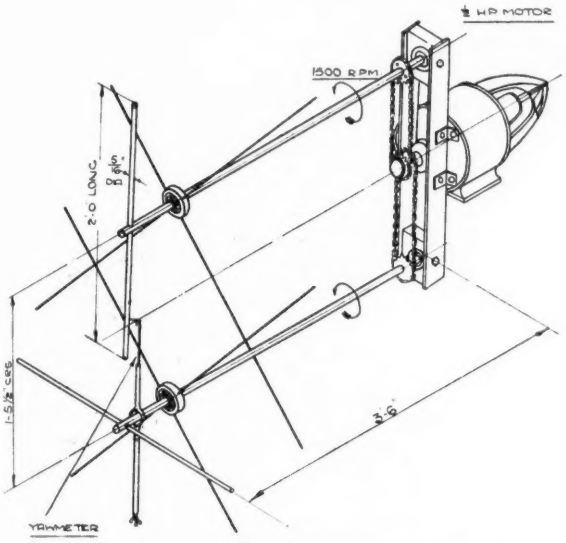

FIG. 20.

General Arrangement of Apparatus for Producing Turbulence.

A number of experiments were made in order to find the effect of turbulence on yawmeter calibrations, firstly, by placing the yawmeter behind gauze of varying mesh, and then by calibrating the yawmeter in the apparatus shown on Fig. 20. The rods passed alternately in opposite directions in front of the yawmeter, so that though the general direction of the air was along the tunnel, the flow would be highly turbulent. In both these methods the same difficulty was encountered, it being found impossible to measure the true mean velocity in the turbulent flow by ordinary means. The velocity, as given by a pitot and static combination, or by the yawmeter used as a velocity meter, showed that the yawmeter calibration was markedly changed by turbulence, while the velocity calculated by the Froude momentum theory, from the decrease of total head at the plane of the gauze or revolving rods, showed that the yawmeter calibration was practically unchanged by turbulence. No conclusive results were obtained

on this point, but it was thought that the velocity head was at fault and that the velocity calculated from the decrease of total head was the most reliable, in which case the calibration in turbulent flow was unchanged.

10 Measurement of Torque Grading

In using these yawmeters to measure the torque distribution along the blades of an airscrew we know that the torque given by the blade elements at radius r is given by the expression

$$dQ = \pi\rho W^2 \sin 2\psi r^2 dr$$

and if at this radius is placed a yawmeter such that its pressure difference, p, is given by

$$p = kx\tfrac{1}{2}\rho W^2 \sin 2\psi$$

then

$$dQ/dr = 2\pi r^2 (p/k)$$

or in non-dimensional form

$$dk_Q/dx = (p/\rho V^2)(\pi/4k) J^2 x^2$$

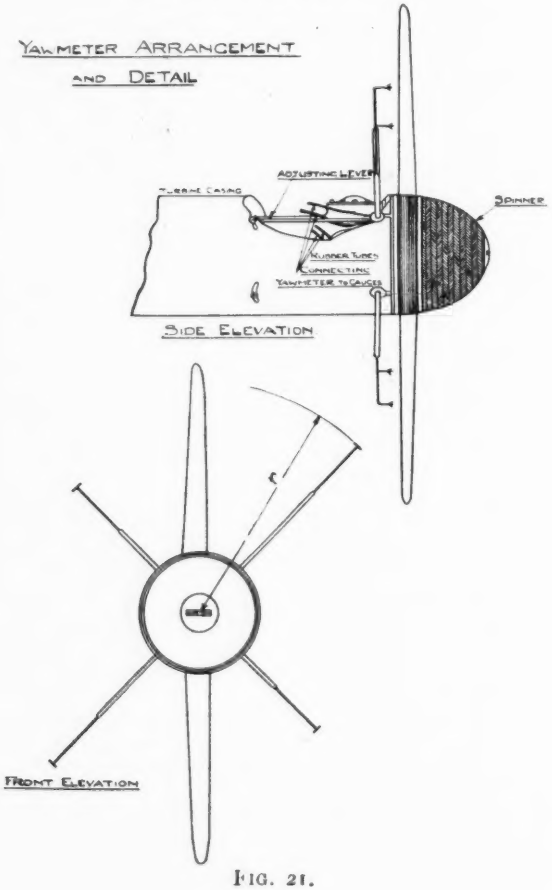

FIG. 21.

The value of dk_Q/dx shows the intensity of the torque grading along the blades and when integrated from boss to tip should give the torque coefficient k_Q.

After some preliminary tests on airscrews running at low speeds which gave very satisfactory results the method was used to measure the torque grading at high speeds of the R.A.F. 31a airscrew to obtain curves corresponding to the thrust grading curves previously shown for this airscrew. The yawmeters were secured to the fairing in a manner that permitted angular adjustment so that each yawmeter could be set accurately along wind. As shown in Fig. 21 the yawmeters were arranged radially at 90° to one another around the turbine axis. Observations were made at eight different radii, four yawmeters being in position at one time. The outer limbs of each yawmeter were connected to the limbs of a U-tube filled with alcohol, and photographic records were obtained of the change in liquid level in the U-tube, and also of the airspeed and of the airscrew's rate of rotation. To damp out the pulsations two inches of capillary tubing were introduced into each circuit. The change in level to be measured varied from 4.4 inches to 0.5 inches and the readings could be estimated to 0.005 of an inch. In making observations the yawmeters were first set along wind. To do this the airscrew was removed, the spinner and boss replaced by dummy fittings that faired into the main turbine casing and the yawmeters were adjusted so that the liquid columns in the U-tubes read the same "wind

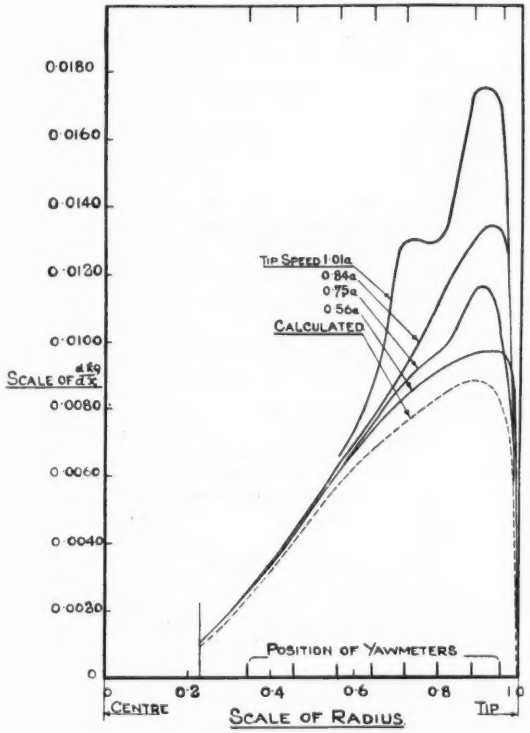

FIG. 22.

Torque Grading Curves R.A.F. 31a Airscrew.
$J=0.25$.

on " and " wind off." Records were then taken with the airscrew and spinner in place and the airscrew working at different speeds of advance. Fig. 22 shows the torque grading curve for the airscrew at $J=0.25$, and the calculated curve obtained from the aerofoil data. The measured grading curves grow rapidly over the tip sections as the speed increases, and the effect spreads in across the outer half of the blade as the tip approaches the speed of sound.

The agreement between the measured torque and the torque obtained by integrating the $dk_Q/dx-x$ curves is shown in Fig. 23, and also the results from

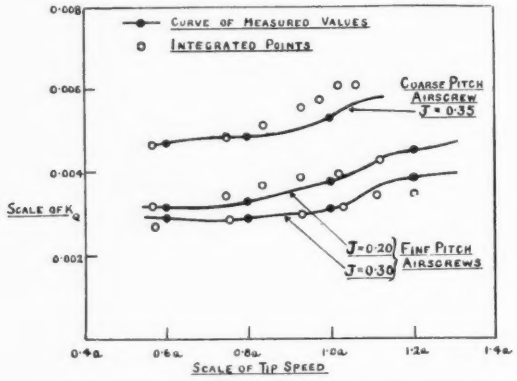

FIG. 23.

Comparison of Measured and Integrated Torque. R.A.F. 31a Section Airscrews.

a fine pitch airscrew of the same section. At low speeds and for the higher J values of the fine pitch airscrew the agreement is very good, but in general the integrated torque at high tip speeds is rather larger than the measured values.

For these tests the yawmeters were about $\frac{1}{4}$ inch behind the trailing edge of the blades; it is possible that the agreement might be slightly improved if this distance were increased. Fig. 24 shows the corresponding curves for airscrews of bi-convex section. Up to the tip speeds of 10 per cent. over the velocity of sound the agreement is well within the limit of experimental error.

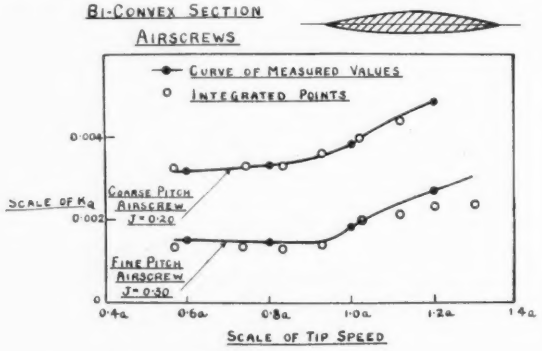

FIG. 24.

Comparison of Measured and Integrated Torque.

11 Twist of Blades

To relate the lift and drag coefficients of the sections to their angles of incidence we must know the extent to which the blades twist under running conditions. The difficulties of measurements are due to the high rotational speed and the general vibration. As any object attached near the tip of the blade would be subject to a centrifugal force of 50,000 times its weight the attachment of a mirror did not seem promising.

The earlier measurements were made using a specially designed electric stroboscope which gave a stationary image of the blade when running up to 12,000 r.p.m. and by mounting a camera to point radially along the blade and focussing on a line at any desired blade section, the twist of that section could be recorded. For the later tests a rather simpler method was adopted. Two polished hemispheres each 0.032 ins. diameter were mounted as far apart as possible on the blade section under observation and illuminated by a "Pointolite." A camera fixed underneath the tunnel floor, in the plane of the airscrew disc, photographed the paths of these hemispheres as they passed through the beam of light from the Pointolite. The distance between the two lines recorded on a photographic plate was a measure of the blade angle, and any variation of this distance was a measure of the twist experienced.

The highest twist value we have recorded occurred on the wood airscrew of Fig. 1. When running at 800 ft./sec. tip speed at $J=0.25$ the twist of the blade section at 0.8 of the tip radius reached a maximum of 2°, the blade angles being increased by this amount. Our twist measurements of the fine pitch steel airscrews of the type shown in Fig. 2 are not yet complete, but the preliminary measurements indicate that the twist is small within the range of our experiments and continues to increase with speed; in almost all cases we have measured the blade has twisted in a direction to reduce the blade angle.

Thus in the case of a model running under maximum load conditions at a tip speed equal to the velocity of sound the twist at 0.8 of the tip radius was found to be of the order of $-0.15°$ for a blade section $12\frac{1}{2}$ per cent. thick and $-0.5°$ for a section 8 per cent. thick. Under similar conditions a full-scale airscrew would twist to the same extent as a model when running at the tip speed if made of the same materials.

12 Calculation of the Lift and Drag Coefficients

The lift and drag coefficients of a blade section can be deduced from thrust and torque grading curves such as have been shown, by using the vortex theory of airscrews (R. & M. 786). For the complete exposition of the theory, reference should be made to Mr. Glauert's original paper. It is shown that if the flow through an airscrew be divided into elementary annuli concentric with the axis of rotation, the flow in any elementary annulus depends only on the blade elements revolving in that annulus and is independent of what is taking place at less or greater radius. If we know the values of the thrust and torque grading coefficients at any radius and the advance per revolution we can calculate the blade section lift and drag coefficients which are those of an infinite aspect ratio aerofoil of the same section. The theory applies strictly to an airscrew with an infinite number of blades, but it is found to give good results even for a two-bladed airscrew provided we do not go too close to the tip. The question also arises as to the extent to which the vortex theory, used for the analysis, applies when the blade velocity is very high. This is unlikely to be a serious matter to the airscrew designer, however, if the thrust and torque grading be measured correctly and the same theory used to design the airscrews as was used for the analysis. The same applies to any other minor limitations in the application of the theory.

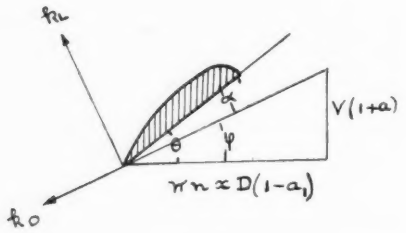

FIG. 25.

We have the following equations:—

$$dk_T/dx = \pi x J^2 a\,(1+a) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

$$dk_Q/dx = \tfrac{1}{2} J \pi^2 x^3\,(1+a)\,a_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

$$\tan\phi = (J/\pi x)\,(1+a)/(1-a_1) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Also

$$dk_T/dx = (B/2)\,\pi^2 c x^2 \sec^2\phi\,(k_L\cos\phi - k_D\sin\phi)\,(1-a_1)^2 \quad . \quad . \quad (4)$$

$$dk_Q/dx = (B/4)\,\pi^2 c x^3 \sec^2\phi\,(k_L\sin\phi + k_D\cos\phi)\,(1-a_1)^2 \quad . \quad . \quad (5)$$

from which

$$k_D = \lambda\,\{\,2\cos\phi\,(dk_Q/dx) - x\sin\phi\,(dk_T/dx)\,\} \quad . \quad . \quad . \quad . \quad (6)$$

$$k_L = \lambda\,\{\,2\sin\phi\,(dk_Q/dx) + x\cos\phi\,(dk_T/dx)\,\} \quad . \quad . \quad . \quad . \quad (7)$$

where

$$1/\lambda = (B/2)\,\pi^2 c x^3 \sec^2\phi\,(1-a_1)^2 \text{ and } x = 2r/D$$

From equations (1) and (2) values of a and a_1 may be obtained, and substituting these values in equation (3), the angle ϕ is obtained. This enables equations (6) and (7) to be evaluated and k_L and k_D for any particular section of the airscrew determined.

The first blade section investigated in this way was R.A.F. 31a. To cover as large a range of incidence as possible two airscrews were used, the one being of much finer pitch than the other. Both were tested over as large a range of J and tip speed as was possible. The thrust and torque grading curves for the portion of the blade between 0.5 and 0.8 of the tip radius were analysed to find the lift and drag coefficients and typical values are shown in Fig. 26. The

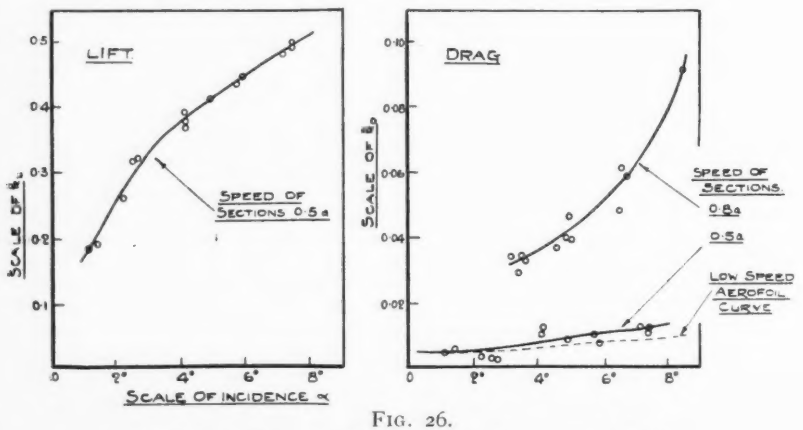

FIG. 26.

Lift and Drag Coefficients from Airscrew Analysis.
R.A.F. 31a Blade Sections.

lift points are very consistent and a good mean curve can be drawn through them. The drag points being deduced from the difference of two quantities of similar magnitude are more scattered. This method of measuring drag is clearly not ideal where low drag must be measured very accurately, but when the drag is large as on the 0.8a curve the method is reasonably satisfactory. Even at the lower speed there is little doubt as to the best mean curve to draw through the points. In the preliminary experiments on a different blade section at low speeds each pressure reading was taken separately and meaned over a period of time and the resulting points agreed well with the aerofoil curve. This is impracticable under high speed conditions, but by taking a considerable number of points well defined curves can be obtained.

A check on the applicability of the R.A.F. 31a lift and drag data to full-scale airscrew design was obtained by using the curves to estimate the torque coefficients of an airscrew of this section on which flight tests had been made. The crosses (Fig. 27) show the full-scale points, the lower curve shows the

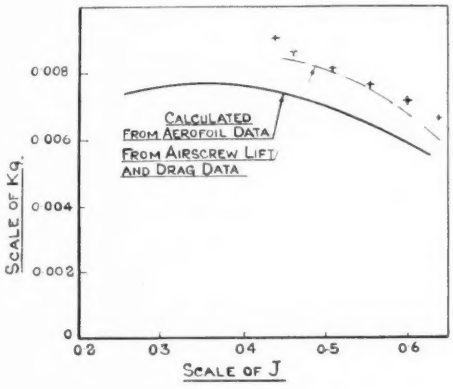

FIG. 27.

Comparison of Calculated K_Q with Full-Scale Results.
+ Indicate Full-Scale Points.

estimate using the ordinary aerofoil data and the higher shows the estimate using the new values obtained from the model blade analysis. The residual discrepancy resembles closely the difference observed for a model Bristol Fighter airscrew when tested alone and in position. The agreement for this section, therefore, appears to be very good.

13 *Lift and Drag of Conventional Section*

The variation with speed of the lift and drag coefficients of the sections we have tested on the steel airscrew have all shown the same general characteristics, but the details of the variations for a conventional airscrew section may interest you more than those of R.A.F. 31a. Fig. 28 shows the variation of k_L with speed and incidence deduced from the tests of a blade section of conventional type, 10 per cent. thick, at 0.8 of the tip radius of the airscrew. The lift curve is slightly above that of the aerofoil at 0.5a; at 0.6a it rises still more at the smaller incidences, but at the larger incidence it begins to fall away. The incidence at which this fall away begins decreases with increasing speed and as the speed is increased the lift values seem to be settling down on a lower line more or less parallel to the lift curve of the original aerofoil. This type of

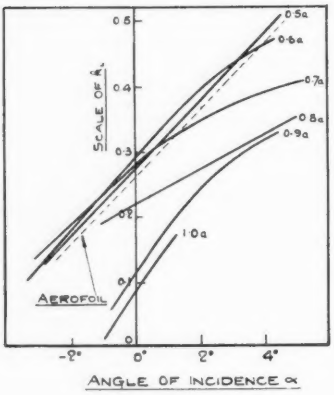

FIG. 28.

Conventional Section.
Thickness 0.1*c.*
k_L *of Section at* 0.8 *of Tip Radius.*
Chord 1.0″.

variation is typical of all the sections we have tested at this radius on the steel airscrews, and offers, I think, the explanation of the phenomena which occurred on the spinning tower test which I mentioned at the beginning of the lecture. In that case the blades were running at low incidence and giving a good thrust at low speeds, but as the tip speed approached the velocity of sound, *i.e.*, when the mean velocity over the working portion of the blade exceeded say 0.8 of the speed of sound the thrust rapidly collapsed, due to the lift coefficients falling on to the lower curve which, at the incidence of the blades, happened to give a mean k_L of zero.

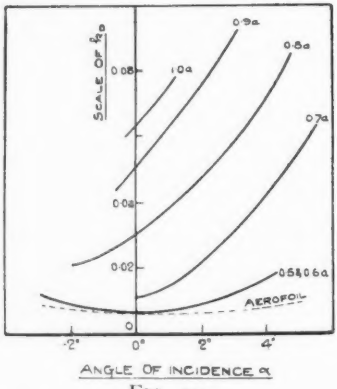

FIG. 29.

Conventional Section.
Thickness 0.1*c.*
k_D *of Section at* 0.8 *of Tip Radius.*
Chord 1.0″.

14 Drag

Fig. 29 shows the corresponding curves for drag showing the rapid rise which occurs with this section when the speed exceeds 0.7a.

15 Scale Effect

Fig. 30 shows the actual experimental k_L values obtained at four-radii when the speed of these sections was 0.7a. It can be seen that the compressibility stall, as the beginning of the fall to the lower line may be called, occurs earlier as the radius is increased and the distance from the tip diminished; as the blades were of taper section this means that the blade sections which have the smaller chord and least Reynolds number stall before those of greater chord and Reynolds

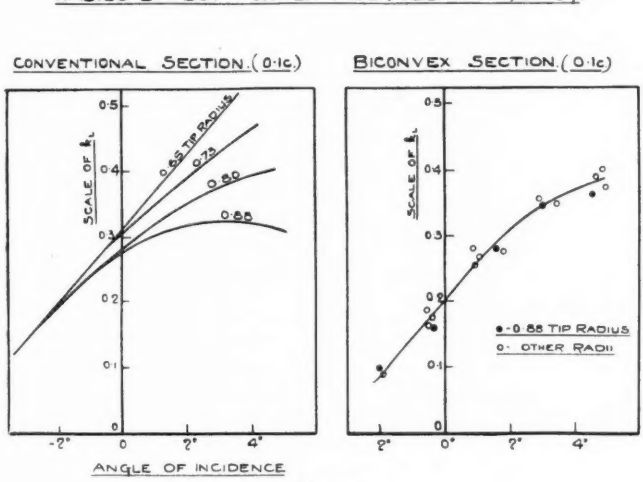

FIG. 30.

number. The extent to which the speed of stall depends on the radius and Reynolds number conditions varies for the different blade sections tested. The effect is scarcely noticeable in the case of the sharp edged bi-convex sections and is large in the case of the conventional sections. In the compressibility stall region the characteristics of these latter sections must be sensitive to the exact test conditions—possibly they depend mainly on Reynolds number or it may be that, in this sensitive condition, their behaviour is influenced by that of neighbouring sections. Until tests are made on the sections using airscrews of different diameter or plan form it will be impossible to separate the effects.

Fig. 31 shows the variation with speed of the lift coefficients of the 10 per cent. conventional section at 0.65 of the tip radius—the innermost radius at which readings were taken. The lift coefficients continue to increase with speed up to 0.8a as was found* for the section of similar thickness percentage, but increased chord at 0.8 of the radius on the wood airscrew of Fig. 1. It thus appears probable that at increased Reynolds number the compressibility stall may occur at a higher speed than is shown in Fig. 28.

* R. & M. 884.

16 *Comparison of Sections*

Our tests are proceeding and until a sufficient number of sections have been tested only tentative conclusions can be drawn. If we take the tan γ values of the sections as the criterion of efficiency we may say that up to 0.65 of the velocity of sound the results of ordinary aerofoil tests give a good idea of the relative merits of the sections. All sections are pretty bad above that speed, and the sections should be as thin as possible to minimise the loss. Up to 0.8a the 10 per

Conventional Section.

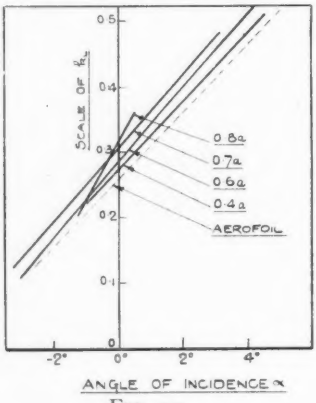

FIG. 31.

Thickness 0.1*c*.
k_L *of Section at* 0.65 *Tip Radius.*
Chord 1.3″.

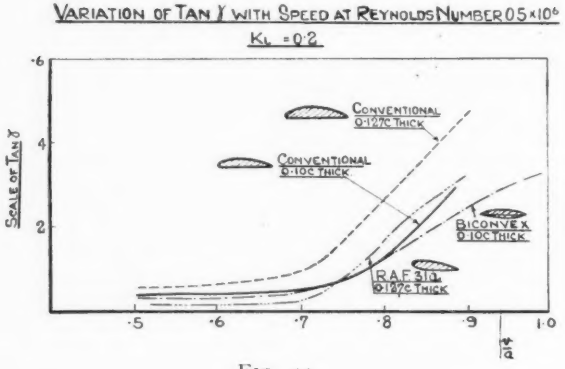

FIG. 32.

cent. conventional section is surprisingly good at the higher Reynolds numbers. For the portion of the blade where the velocity exceeds 0.8 of the speed of sound a sharp-nosed section may have advantages. Fig. 32 shows some typical results; at 20 per cent. higher Reynolds number the 12.7 per cent. conventional section at 0.8a is falling to the level of the R.A.F. 31a curves while the 10 per cent. conventional section and bi-convex sections remain constant.

17 *Review of Methods*

The thrust grading over the working portion of the blades of an airscrew running at high speeds appears to be capable of convenient measurement by the pitot tube method, any discrepancies between the measured and integrated values being practically within the limits of experimental error. The same may be said of the corresponding method which has been developed to measure the torque grading, but the yawmeters need care in use and it would be an advantage if a type were available combining the advantages of the present type with complete freedom from scale effect.

The thrust and torque grading results can be analysed to give the lift coefficient of the blade section at any incidence and also the general magnitude of the drag coefficient. It is estimated that the experimental error in the lift determinations seldom exceeded 2 per cent. except at the higher speeds where the thrust on the blade element was unsteady, in which case the uncertainty might be as much as 5 per cent. It is estimated that the experimental error in the value of a drag coefficient could vary from 0.003 at small drags to 0.006 at large values when the drag coefficients were of the order of 0.1. These are the estimated errors of single observations and should be considerably reduced by the faired curves through them. In comparing this method with that of a high speed wind tunnel as a means of finding the properties of a section to be used in high speed airscrew design it should be remembered that the corrections to drag and incidence for tunnel constraint are uncertain in a high speed tunnel. Hence, although comparative drag figures can be obtained to higher accuracy the actual magnitude of the drag coefficients may be more uncertain than with the airscrew method. As regards initial cost the airscrew method is certainly the cheaper, especially if a tunnel is already available; if the tests must be made at high Reynolds number the cost of a high speed tunnel would be prohibitive. As regards tunnel time the complete data for the analysis of the properties of the blades of an airscrew can be obtained in an afternoon, although the subsequent analysis takes some time. As regards cost of models, however, the construction of an airscrew to run at these speeds entails more work than the construction of the corresponding aerofoil for test in a high speed tunnel.

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R. & M. 962.* "Measurement of torque grading."—Douglas and Coombes.

R. & M. 1086.* "Characteristics of R.A.F. 31a at high speeds."—Douglas and Perring.

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R. & M. 1124.* "Characteristics of a conventional airscrew section at high speeds."—Douglas and Perring.

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N.A.C.A. 207. "Aerofoil characteristics at high speeds."—Briggs, Dryden and Hall.

N.A.C.A. 255. "Pressure distribution over aerofoils at high speeds."—Briggs and Dryden.

* The subject matter for this lecture is mainly taken from these.

Discussion

Mr. McKinnon Wood (of the R.A.E.) said that the work described in the paper had been very largely individual work by Dr. Douglas, with the assistance of junior members of the staff—Mr. Coombes, Mr. Perring and others. This model work did not start by deliberate design. Model experiments were instituted as a precautionary measure before doing the full-scale experiments to which Dr. Douglas had referred. Then it was thought that it would be a good thing to include thrust and torque meters; then pitot tube measurements were taken, and it was gradually realised that the wind tunnel method was really the best method by which to attack the problem. While the model test was being prepared, instructions were issued that the full-scale airscrew was not to be flown at full r.p.m., but it was flown up to full revolutions by Squadron Leader Hill with Mr. Stevens, and nothing serious happened. The speaker made the subsequent full-scale observations. He had been impressed by the terrific noise of the airscrew as the aeroplane passed overhead, but he was surprised to find, when in the aeroplane, that it appeared to be no more noisy than any other. That was in accordance with Major Tucker's experience and the theoretical deductions, that the noise was concentrated in the plane of the airscrew. The yawmeter method of measuring the torque grading was a comparatively late innovation, and the development of a satisfactory yawmeter had entailed a great deal of work; that development and the method of measuring the twist in an airscrew rotating at about 14,000 r.p.m. were due entirely to Dr. Douglas.

With regard to scale effect, Mr. McKinnon Wood said he had been brought up to think that this occurred at small Reynolds numbers, and then conveniently disappeared. He would like to warn students, however, not to believe that, because it was a very dangerous notion. Some two or three years ago he had consulted Sir Thomas Stanton on the question as to whether there was any evidence of the effect of Reynolds number at the high value at which they had been working in these experiments; Sir Thomas had thought it extremely unlikely that the effect they were investigating would not be purely the effect of compressibility, and everybody seemed to be of that opinion. He believed they had proved fairly definitely that there were important scale effects in the region where the flow over the aerofoil was breaking down, where the lift curve, which was getting steeper as the speed went up, suddenly started collapsing on to a lower curve. It was unfortunate that there should be this scale effect, because they had now developed a full technique of testing at high speeds, and if the results were very different full-scale, and if they could not by, say, doubling the size of the models, obtain the same results as at full-scale, they would be forced to extensive full-scale experiments in order to get accurate data. With some sections, as, for instance, the conventional airscrew sections, the scale effects were very serious, but with others, notably the bi-convex section, the scale effect was almost imperceptible.

The average pure scientist was happy so long as he was getting definite information, and he did not really worry as to whether his information was leading to improvements in design. If he were proving that to run airscrews at high tip speeds was to waste an enormous amount of power, he thought he was doing a useful piece of work, but the practical engineers and aircraft designers were apt to feel that he had not done anything. The scientist's attitude was perhaps the fairer one. The aeroplane designer would want to know whether all the work which was now being done was really leading to something which would enable us to get higher efficiency in airscrews running at very high tip speeds. A little while ago it had looked as though one section was as bad as another, but now there seemed to be indications that we might be able, not to get better airscrew efficiencies by working at these high tip speeds, or even to get efficiencies as good as those obtained with lower tip speeds, but to get at

high tip speeds efficiencies not so very much less than the efficiencies obtained at lower speeds. Mr. Glauert had recently predicted theoretically the amount of steepening of the lift curves as the speed increased. He had also pointed out that the curves, at some speed, began to collapse and ultimately fell on to a curve with zero no-lift angle (measured from the chord through leading and trailing edges). If one used a section which had a zero no-lift angle to begin with, the curve presumably would not collapse in that way. There was a very big increase in drag occurring at the same time as the collapse of the lift curve, and with a section which could not collapse from one lift curve to the other one might not get the large increase in drag. That was the line on which the experimental work was proceeding at the moment, and there was already some indication from it of the possibility of improving the efficiency of airscrews at high tip speeds.

Dr. H. C. Watts expressed admiration for the experimental technique which was evidenced by the paper. Not only had the experimenters, he said, to measure the thrust and torque of an airscrew, which was a comparatively simple matter nowadays, but they had had to measure the thrust and torque grading along the blade. They had had to find out whether the airscrew was twisting, and had had to be sure that the torque they were measuring was the real torque and was not affected by the reaction of the slipstream on the apparatus. Those who knew something about the experiments in the early days might well be excused for doubting, as some of them had done, whether the difficulties would really be surmounted. To some of those present it might be a surprise to find how drastically the thrust and torque of an airscrew fell off at high speeds, and it was a matter which had been worrying him, as well as other airscrew designers, for some years. Before and during the war they were fairly happy and self-confident; they had thought they could estimate to within half per cent. of the efficiency one might expect from an airscrew, and had even presumed that an engine was not of sufficient power if it did not turn the airscrew at the speed they had expected. Experience, however, had made them sadder and wiser men. They began to get into trouble in design when airscrews began to run at tip speeds within the range of 800 and 900 ft. per second; the airscrews ran slow. They were underestimating the torque coefficient, and aircraft designers had told them that they were not getting the efficiencies expected. The airscrew designers had introduced all sorts of empirical corrections and had managed to get correct results for the time being, but the confidence with which they answered questions concerning efficiencies varied inversely with their experience. Then Mr. Glauert had developed his vortex theory of airscrews, which seemed to be sound; the Aeronautical Research Committee had tested a whole family of airscrews, and judged by the results Mr. Glauert's theory seemed to be almost perfect. That theory, however, did not give correct results on modern airscrews. When the family of airscrews was tested, he had deliberately designed an airscrew direct from that family, and had checked it with the vortex theory, but when tested it ran about 200 revs. too slow. Obviously, the torque coefficients were badly under-estimated. Then, following subsequent discussion of the problem, the Royal Aircraft Establishment had started to investigate the matter; the manner in which they had tackled it was now known, and he was glad of the opportunity publicly to express his admiration. The present paper might be called a first instalment; Dr. Douglas had plenty more to come, and whether he gave it in another lecture to the Society—as it was hoped he would—or not, the results would be available through the usual channels. The Aeronautical Research Committee were working on this investigation along three lines—one being pursued at Cambridge, another at the National Physical Laboratory, and another at Farnborough. The first two were not yet sufficiently developed for anything to be said about them, but the third had been described by Dr. Douglas in his paper. So far as the Aeronautical Research Committee had had anything to do

with these experiments, their argument was that the airscrew designer was not in a position at the present moment to design with any confidence an airscrew suitable for engines running at the speeds attained to-day, and he could not do it because he did not know what aerofoil characteristics to use for these high tip speeds. Therefore, the first thing to do was to examine the ordinary old-fashioned conventional section, and to find out the lift and drag coefficients for those sections at high tip speeds. He would then be on safe ground, and would be able to design accurately, even if he did not design the best. The second thing to do was to try to find out what was the best section to use at these speeds. The first part of the work had now been done, and Dr. Douglas was busy on the second. To some extent it was guess work, though very intelligent guess work; one could only suggest a section and try it in order to see if it were any good, and it was hoped that the lines of research being pursued elsewhere would help to decide what was likely to be a good section. He had every confidence that before long the airscrew designer would regain his self-confidence.

Mr. LYNAM, as one who had been closely associated with Dr. Douglas and his work since its inception, said it was quite clear from the paper that a long series of difficulties had to be overcome; they had been overcome very successfully and Dr. Douglas was to be highly congratulated upon having placed before airscrew designers some very valuable data of a kind to which they had not previously had access. The discrepancies which had occurred at different times between the calculated and the actual performances of airscrews, as mentioned by Dr. Watts, had been due to a number of factors. A great step forward had undoubtedly been made as the result of the development of the vortex theory of Glauert, coupled with the adoption of a symmetric plan form, which had eliminated, or very much reduced, the twist of the blade. It was then found that the vortex theory did give an adequate explanation of the performance of the family of airscrews tested in the wind tunnel. They were metal screws of a form which could not twist very much, tested at low tip speeds, and the analyses of the airscrews agreed well with the measured performance. He believed that if one used the symmetrical plan form, and the speeds were not above .6 or .7 of the velocity of sound, one could predict the performance of a full-scale airscrew with very fair accuracy; it was only when very much higher tip speeds were reached that discrepancies would arise. With regard to compressibility effects, he said these, of course, depreciated the L/D value of the section. The L/D value of the section, or the aerofoil efficiency, was not the only factor affecting airscrew efficiency, however. The helix angle, or pitch/diameter ratio, also played an important part, and the effect of high tip speeds in reducing efficiency was very much greater with screws of fine pitch/diameter ratios. He was inclined to think that in the case of the very coarse pitch airscrews, such as were used in the Schneider Trophy race, the tip speeds of which were above the velocity of sound, the losses due to these effects were small, but the effect of high tip speeds on fine pitch/diameter ratio airscrews was very important. There were two aspects of the work described in the paper. In the first place, it provided the airscrew designer with valuable data which would enable him to design airscrews for high tip speeds in a very much better manner than he had been able to do before. On the other hand, the paper might be regarded as giving a word of advice to engine and aeroplane designers that high tip speeds were to be avoided where possible. With regard to the twist of the blades, he said Dr. Douglas's measurements had shown that at the very high tip speeds reached in these experiments, the twist of the wooden screw was only 2° and 0.2° with metal. That twist was due mainly to centrifugal force, and its small magnitude was due largely to the shape of the blade, which shape was based entirely on the theoretical work of Dr. Griffiths of several years ago, which showed the symmetrical form to be the only form in which the torsion of the blade could be neglected. Referring to Dr. Douglas's curves showing the effect of scale on the

conventional sections at high speeds, Mr. Lynam asked if there was any scale effect on drag, and if so, what was the effect of scale on L/D. It would appear that if there were no effect on drag, we were not doing right in making airscrews with very narrow tips, and he would like to know whether Dr. Douglas considered that broader tip airscrews would be more efficient at high speeds.

He remarked that the noise emitted by airscrews at high tip speeds was very great indeed and very penetrating. The noise could be heard at long distances, particularly in the plane of rotation, even when there were intervening buildings. The noise emitted by the airscrews is a great handicap in military aircraft in affording as it does, a means of detection and a great discomfort to the passengers in civil machines. This noise could be reduced only by using the lowest possible tip speeds and stiff blades.

Mr. R. K. PIERSON: I think that the question of tip speed has been very much neglected. It is a pity that it has not been possible to carry out a programme of full-scale research at the R.A.E. as I consider that wind channel work should always be checked by comparative full-scale tests.

As a result of analysis of flight tests at Weybridge on two or three machines, we have been able to deduce a curve of tip loss against tip speed for our ordinary timber propellers, and also for metal propellers with thin tip sections. If our tests can be relied upon, we found that the loss was not as severe as that reported in R. & M. 884. We found that the loss on timber propellers was not appreciable below 750 ft./sec. tip speed, and on metal blades 900 ft./sec. were permissible.

As for the actual loss we found:—

	At 900 ft./sec.	1000 ft./sec.
Metal (our own)	1%	$2\frac{1}{2}$%
Timber	4%	8%
Model test, R. & M. 884 (R.A.E.) ...	11%	17%

The loss, whatever its actual magnitude may be, is responsible for some interesting effects on performance. On a certain military machine of our design, which was fitted originally with a direct-drive engine, we obtained an increase of speed of 20 miles per hour by having a gear fitted to the engine, the tip speeds being 1,060 and 840 ft./sec. respectively. Both propellers were of timber, but of course all this gain was not entirely due to the reduction of tip speed, but also to the reduction of slipstream velocity over the body and to increase of pitch/diameter ratio.

As regards the commercial machine, if a tip speed of 930 ft./sec. is indulged in for cruising, then 4 per cent. of the engine power is wasted in the production of noise, and 4 per cent. of the petrol is entirely unproductive.

The question of noise is very important from the commercial point of view. It is useless to go to great trouble to silence exhaust and tappets, unless the propeller noise is eliminated. This is particularly important in multi-engined machines, where the passengers generally sit close to the plane of rotation of the propellers, where the noise is most severe.

The proper cure for a commercial machine is the provision of an engine gearing which will permit of a tip speed of less than 750 ft./sec. The main disadvantage of this lies in the large propeller diameter necessary, owing to its slow speed.

I believe that a certain amount can be done by design of the propeller tip. The latest American propellers use a tip section of camber/chord ratio as small as .07—smaller than that used on the model at the R.A.E. It would be interesting if propellers of thinner tips could be tested at the R.A.E.

Mr. J. D. COALES: There is some uncertainty in my mind as to whether the pitot tubes used for observing the thrust and torque grading really measure all that goes to make up the thrust and torque of an airscrew when its blade elements are moving at speeds above the velocity of sound. Everyone is familiar

with the photographs of the bow and stern waves originating from a bullet moving through air; and similar waves must be caused by the leading and trailing edges of an airscrew blade. These waves will have helical fronts. Those on the forward side of the blade will move upstream and those on the after side downstream at velocities much greater than the forward speed of the airscrew, the velocity normal to the wave front being the velocity of sound. The pitot tubes behind the airscrew will be quite unaffected by the upstream waves, and may or may not correctly measure the thrust and torque due to the downstream waves. Thus at least part of the thrust and torque due to "tip speed losses" will be missed by the pitot head measurements. Even at speeds below that of sound, provided the compressibility effects are not negligible, it seems to me probable that pitot head measurements will not give complete data of the thrust and torque grading when "tip speed losses" are considerable.

Dr. Richardson said the variation of the lift curves at speeds approaching that of sound had interested him most, and he asked if Dr. Douglas had any fundamental explanation of the curves he had obtained. He supposed the effects were related to the bow wave referred to by Captain Coales. An object moving at a velocity above that of sound would have to generate those waves, and it would require extra energy in order to do that, which would be manifest in increasing drag, and possibly the falling off of the lift might be explained by the formation of the wave, because it would tend to equalise the flow below and above the aerofoil and make it like that round a symmetrical body, reducing the "circulation." It might be interesting to compare the drag resistance of an aerofoil with the resistance of a projectile at the velocity of sound. He believed there were data available to show how the drag resistance of a projectile varied when its velocity was above or below the velocity of sound. He presumed that in applying the principle of dynamical similarity to the observed changes on the coefficients at high speeds, the compressibility had been introduced as an additional factor as well as the usual velocity, linear dimension and viscosity forming the Reynolds number, applied to low speed scale effects? Finally, Dr. Richardson congratulated Dr. Douglas upon the ingenuity he had displayed in the design of his apparatus.

Mr. Capon said that a point of interest in connection with this work was the ingenious manner in which the difficulties had been overcome one by one as they appeared, and the natural and logical development of the whole subject. He agreed with Mr. Pierson that full-scale tests appeared to be required. There was a scale effect which might lead to a difference between the calculated results for a particular airscrew and the actual results obtained, and probably the only way to check that was to measure at full-scale. That was already being done, he believed, in the United States, in their 20ft. tunnel, using full-scale airscrews running at very high tip speeds. At the R.A.E. they were contemplating the carrying out of some full-scale experiments. The work would be very difficult, and he did not know whether the accuracy obtainable from the experiments would give a very satisfactory full-scale check.

Mr. L. P. Coombes, referring to the statement by Mr. Lynam, that in coarse pitch airscrews the tip speed was not so great as in fine pitch airscrews, said that, nevertheless, the loss in the former was quite serious. Tests on the loss of efficiency in airscrews running at tip speeds between 900 and 1,100 ft. per second had been made, and such preliminary results as had been obtained so far were in very good agreement with Mr. Douglas's predictions, but there had not yet been an opportunity to make really exhaustive tests. He did not believe that in every case the tip speed of an airscrew could be reduced. In some cases the gear ratio was limited, not only for mechanical reasons, but by take-off conditions, especially in the case of seaplanes. One could not gear down the airscrew too much, as the blades of a very coarse pitch airscrew would be so badly stalled

that the aircraft would not take-off, so that very high tip speeds would be attained with modern engines. Therefore, such work as Dr. Douglas was doing, and which would put the matter on to a sound theoretical and calculable basis, was going to be very valuable.

Mr. W. G. A. PERRING: Since the real object of the experiments described this evening was to obtain lift and drag data for aerofoil sections moving at speeds commensurate with the speed of sound, it may at first sight appear strange that the results have been obtained by a somewhat circuitous method. The obvious and most straightforward manner in which to obtain the desired data would seem to be from tests on aerofoils in a high speed tunnel either of the closed or open jet type. This alternative method, however, is not without serious practical difficulties, and the results on aerofoils, obtained from such tunnel tests, would necessitate corrections for tunnel constraint and aspect ratio; corrections, that at present are only known for relatively low speeds, where compressibility effects are absent. In America an attempt has been made to measure the lift and drag of an aerofoil at high speeds placed in an open jet. The jet was a little over 12in. in diameter, and the aerofoil spanned the jet completely. To maintain the speed of sound in a jet of this size necessitated an input of 5,000 horse-power at the compressor end, so that on a horse-power basis, the airscrew method with its 60 horse-power air turbine, and about 300 horse-power tunnel is a decidedly more economical proposition.

Experimentally the difficulty of the tunnel method would be to obtain a uniformly steady stream. Photographs of the discharge of air from nozzles at speeds around the velocity of sound show that standing waves are set up in the issuing jet, and the presence of standing waves would be a difficulty accompanying all experiments in jets (or tunnels) working near the velocity of sound. Uniform flow in air streams moving with speeds near that of sound, appears to be rather unstable, and even if steady flow conditions exist, it is probable the introduction of an aerofoil into the stream would react on the flow and set up the standing waves of the alternative type of motion.

Whilst the airscrew method avoids this difficulty, there is another difficulty which so far as actual values of lift and drag is concerned, is peculiar to the airscrew method only, viz., the validity of the vortex theory when applied to airscrews moving at high tip speeds.

If the ordinary vortex theory breaks down at high speeds, then clearly a modified airscrew theory will be required before aerofoil data obtained from jet or tunnel tests can be usefully applied to the design of full-scale airscrew. On the other hand, with our present knowledge of the subject, the airscrew method of obtaining lift and drag possesses this further advantage, that provided the same theory is used when applying the results to "full scale" as was adopted during the analysis of the grading experiments, then any errors in the theory will largely counterbalance one another.

And now just a word on "scale effect," which is usually characterised by Reynolds number VL/ν. Since ν is constant it will depend upon the product $V \times L$, and if the forms are geometrically similar and V/a is constant, then it will depend entirely upon this product. Widely different "scale effects" were obtained with the three sections R. & M. 322 No. 3, R.A.F. 31a, and the biconvex discussed in the present paper. Compressibility effects commence first at the nose of an aerofoil, so that in all probability the best length dimension L characterising the scale effect in the product $V \times L$, is one chosen to define the shape of the upper surface near the nose. The results for the sections given in the paper indicate that when the product VL (using the radius of curvature of the upper surface near the nose) is low, scale effect is considerable, and that the amount of "scale effect" diminishes as this product increases; this of course is always true for geometrically similar sections, but it appears to apply at least

approximately to dissimilar sections. The only general conclusion that can be drawn from the experiments so far published is that for efficiency at high speeds the sections must be as thin as strength considerations permit; sharp-edged sections appear profitable at the speed of sound, but whether ultimately the best section will be symmetrical, and if symmetrical, sharp-edged, must be left for some future research to decide.

Mr. Lock: The problem of the motion of a body in a fluid was of great interest; the motion of a body in a compressible fluid was one of the most difficult problems to deal with and was practically untouched on the theoretical side. The only work involving detailed calculations on the subject had been due to the late Lord Rayleigh until the recent paper by Mr. Glauert, which latter had carried the subject a considerable stage further. The subject of the motion of bullets and shells in the air had been studied by gunnery experts for many years. They would probably consider that the scientific development of the motion of a bullet must be at least 50 years old, yet the gunners had hardly reached the state of knowledge, he believed, that Dr. Douglas had reached in ten years. The experiments in gunnery had shown the existence of a wave, and the question of whether such a wave was formed or could be formed in the case of an airscrew was a very interesting one. It seemed to him to be possible that, owing to the fall of the velocity inwards along the blade, this wave or bore might not be formed in the case of an airscrew however high the speed up to, at any rate, appreciably above the velocity of sound, and that was a point upon which a comparison with wind tunnel experiments might throw great light, because it seemed to him that in the high velocity wind tunnel this bore must be formed. The existence of a bore was predicted, on theoretical grounds, by Lord Rayleigh, and the results he had obtained many years ago had given the standard method of determining velocity in a high speed jet, his formulæ having been fairly recently verified exactly by Sir T. E. Stanton.

Mr. P. J. Ralli: Those among us who, like myself, are working in private industry do not usually have the opportunity of carrying out or witnessing such a comprehensive series of tests which are particularly valuable on account of their great generality (Mr. Douglas has been able to present his results almost entirely in the form of non-dimensional coefficients). Here, therefore, is an instance where we, in the industry, have reason to appreciate very highly the patient research work involved.

As an example of full-scale corroboration of the lecturer's conclusions it may be of interest to quote some early observations made by the Fairey Aviation Co. three or four years ago. A direct drive Napier Lion Engine was substituted for the standard geared Lion in a general service seaplane. No alterations whatever were made to the aircraft beyond those necessarily involved in the conversion of engines. The geared propeller was 12ft. 0in. in diameter and a first trial on the direct drive was made with a diameter of 11ft. 0in. The tip speed actually attained was 1,260 ft./sec. and the loss of speed of the aircraft was 32 m.p.h. The next step of course was to reduce diameter, but no tolerable results could be obtained above 9ft. 0in. when the tip speed was about 1,080 ft./sec. and the speed of the machine within 9 m.p.h. of that obtained with the geared engine; a further 3 m.p.h. were obtained by fining the tip sections.

From these tests and similar ones on subsequent machines a curve of efficiency against tip speed was derived which is very similar in character to the one presented by Mr. Douglas.

I agree with Mr. Lynam that since L/D is of comparatively small importance at high values of J the losses should not be as important in most modern aircraft as they appear to be on the model tests; I think, however, that this feature will appear of its own accord if Mr. Douglas's results are extended by calculation to

large values of J, and that there is no reason to assume any fundamental change in the results he has found at small advances per revolution.

The revelation of the influence of Reynolds number as having a marked influence on the aerofoil characteristics quite apart from the value of v/a is extremely interesting.

I should like to suggest that a special series of tests specially staged to investigate this effect more fully, say at constant values of v/a, would be valuable.

As regards the effect of tip speed alone, I think the subject has now been very satisfactorily explored as far as the designer's interests are concerned.

I do not think I can put any questions to Mr. Douglas without anticipating on the further contributions on his part which have been foreshadowed in the course of this discussion. I can only say that I am looking forward to these as I feel sure they will be of the greatest practical value.

Reply to Discussion

In reply to Mr. Lynam, in the case of the conventional sections, the results suggest that increase of scale delays the compressibility stall and probably also delays the increase of the drag coefficients with speed, but the drag changes with scale are less marked and are partly masked by the lower accuracy of the drag readings. Within the range of Reynolds number covered by our tests the scale effect on lift and drag both combine to improve the L/D values with increase of Reynolds number and where any section is on the point of stalling an increase of chord would delay the stall and improve the efficiency.

The results of Mr. Pierson's full-scale measurements are of great interest. I consider, however, that our model results are in better agreement with his full-scale tests than he indicates. The full-scale figures given show the extent to which the efficiency fell off when the tip speed was increased from, say, 750 ft./sec. to 900 ft./sec. and then to 1,000 ft./sec., whereas the model figures from R. & M. 884 show the reduction of efficiency which occurred when the model tip speed was increased from about 190 to 900 and 1,000 ft./sec. The model results of R. & M. 884 are shown by the continuous line in Fig. 10 and it will be seen that the efficiencies at 900 and 1,000 ft./sec. are 94 and 89 per cent. respectively of the efficiency at 750 ft./sec. giving losses of 6 and 11 per cent. which can be compared with Mr. Pierson's full-scale values. Probably the estimated curve at $J=0.7$ corresponds more closely than the 0.35 values to the full-scale conditions, and in this case the corresponding losses would be 4 and 7 per cent.; these agree very closely with Mr. Pierson's results on wood airscrews.

As regards the criticisms of Dr. Coales regarding the use of the pitot yawmeter method of measuring the thrust and torque grading at high speeds, I can only say that the method used is reasonably sound at low speeds and, judging from the agreement of the direct measured thrust and torque with the integrated values, it gives reasonable results even when the velocity of a section slightly exceeds that of sound. The speeds in which the designer is at present most interested and for which we are endeavouring to supply design data, are those immediately below the velocity of sound where the question of a bore does not arise.

A discussion of Dr. Richardson's question as to the reasons for the lift variations at high speed is given in Mr. Glauert's recent communication to the Royal Society. As the speed increases the influence which the blade is able to exert on the flow ahead of itself decreases so that the exact blade shape becomes of less importance and the lift coefficient tends to collapse approximately to that

of a section symmetrical about its chord. Regarding his further question the characteristics of an aerofoil at high speeds are functions both of Reynolds number and the compressibility ratio v/a and it is necessary to arrange the experiments so that the one is kept constant while the other is varied.

Mr. Lock's remarks with regard to the bore are very interesting; it should be possible to photograph the bore if there is one.

With regard to the point raised by Mr. Ralli and others, that tip losses may be of minor importance, when the advance per revolution is large, the reduction of loss is to a great extent neutralised by the fact that the average speed of the blade in relation to the air is much higher on account of the comparatively higher forward speed. Thus, if a blade running at a given tip speed—and by this is meant the rotational component of the speed—has a large advance per revolution then, on compounding the two velocities, the velocity of the blade relative to the air is considerably increased, consequently the drag coefficient increases and reduces the gain which might be expected from other considerations.

In conclusion I wish to thank the various speakers, on my own behalf and of those who have worked with me, for the appreciation they have expressed.

On the motion of the CHAIRMAN, a hearty vote of thanks was accorded Dr. Douglas for his paper.